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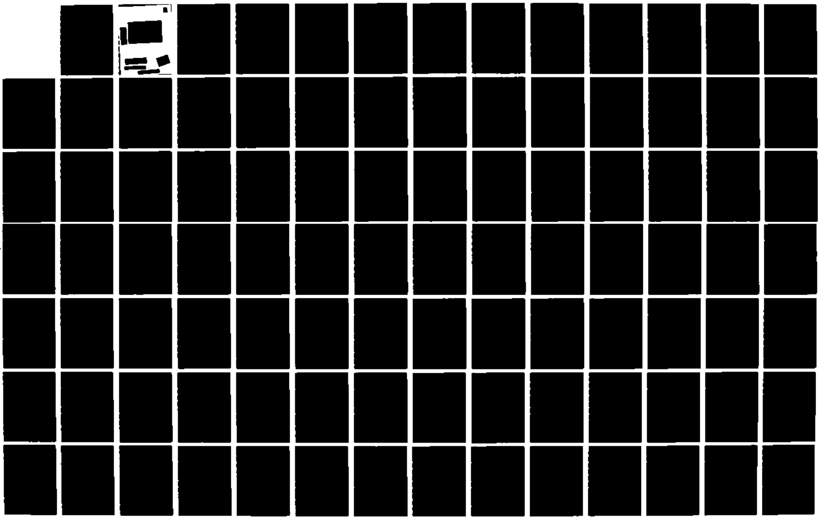

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CAMBRIDGE, MASSACHUSETTS 02139

QUALITY ASSESSMENT OF GLASS REINFORCED
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BY
RONALD DAVID THOMAS
AND
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N66314-70-A-0073
XIII-A

JUNE 1985

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by

RONALD DAVID THOMAS
B.S.M.E., Purdue University (1977)
and
CHRISTOPHER WHEELER CABLE
B.S.M.E., United States Naval Academy (1979)

Submitted to the Department of
Ocean Engineering
in Partial Fulfillment of the
Requirements of the Degrees of

OCEAN ENGINEER
and
MASTER OF SCIENCE IN MATERIALS SCIENCE AND ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Signature of Author: Ronald D Thomas
Department of Ocean Engineering, 7 May 1985

Signature of Author: Christopher W. Cable
Department of Ocean Engineering, 7 May 1985

Certified by: John F. Mandell
Dr. John F. Mandell, Thesis Supervisor
Department of Material Science and Engineering

Certified by: F J McGarry
Professor ~~Fredrick~~ McGarry, Thesis Supervisor
Department of Materials Science and Engineering

Certified by: W David Whiddon
Associate Professor William D. Whiddon, Thesis Reader
Department of Ocean Engineering

Accepted by: A. Douglas Carmichael
Professor A. Douglas Charmi~~chael~~, Chairman
Ocean Engineering Departmental Graduate Committee

Accepted by: Bernhardt Wuensch
Professor Bernhardt Wuensch, Chairman
Materials Engineering Department Graduate Committee

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ABSTRACT

The requirements for quality assessment of Glass Reinforced Plastic (GRP) hulls in advanced performance naval ships have been studied.

Important features of a Quality Assurance (QA) plan which could support a lower factor of safety structural design are explored. A survey of industry QA plans was used to identify significant management attributes. A methodology to develop important technical attributes and effectively engineer the QA plan to any GRP ship is presented. This methodology is then applied to a specific ship. A recent feasibility design of an advanced Minewarfare Ship (MWSX), which was performed by the authors, is used as the example.

The effect, detection and evaluation of defects is emphasized. Using existing models and a fracture mechanics analysis, the effects of key defects have been quantified. Cracks in the edges of hull penetrations are shown to be critical defects that have not previously been considered important. Additionally, an equivalency between key defects for typical design loadings is demonstrated. This equivalency is important in order to correctly proportion the efforts to control and correct defects.

An integrated detection plan is proposed. Several testing and monitoring techniques are combined during various stages of construction and during the life of the ship. Unique aspects of this plan are the use of a bending proof test on a full scale prototype hull and the use of acoustic emission as a continuous, in service monitoring

technique.

Example evaluations of typical defects are made based on current standards and procedures. The results are compared for consistency to the estimates of the effects of defects previously derived. The lack of guidance on the hole with cracks defect is considered to be a major shortcoming of current standards that must be adequately addressed before a lower factor of safety design can be realized.

Detailed recommendations for further research and development needed to advance the science of QA for GRP ship hulls are provided.

Thesis Supervisors : Frederick J. McGarry and John F. Mandell
Title : Professor of Polymer Engineering
and Civil Engineering,
and Principal Research Associate

ACKNOWLEDGEMENTS

We would like to thank the U.S. Navy for sponsoring our studies at M.I.T. We would also like to thank: Thesis advisor, Professor Fredrick McGarry for his early inspiration and dedicated teaching. No matter how busy, he always had the time to sit down and talk to us. Thesis advisor, Dr. John F. Mandell for his technical guidance and moral support. Associate Professor William D. Whiddon, our thesis reader, for providing early organizational guidance for this thesis. We also thank the following people who helped make this thesis a reality: Professor Paul Lagace for providing technical guidance in the area of composite structures along with a good sense of humor, Arthur Rudolph for machining our test specimens, CDR Terrence Tinkel, USN (Ret) for providing the initial guidance that led to this effort, Alan Kurzweil for providing technical guidance in the area of GRP ship structures, and John M. Keller for assisting in thesis graphics. Finally, we thank the following personnel from Naval Sea System Command for providing the necessary funds to perform this work: CAPT John Young, George Sweger, Bob Johnson and Paul Skolaski.

Author, Ron Thomas, would like to thank his wife, Dot, whose patience, sacrifice, understanding and encouragement led to the successful completion of this thesis, and his children; Stacey, Kimberly and Ronnie who provided many

hours of joy and much needed distraction during this endeavor.

Co-author, Chris Cable, thanks God and his family for the real inspiration for this thesis.

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3.1 QUALITY ASSURANCE BACKGROUND

In the earlier days of the U.S.Navy, quality was attained soley by the quality of materials and the craftsmanship of the worker, followed by an inspection of the finished product. This was an acceptable method in that the vessels and their systems were quite simple, defects in workmanship and procedures were quite easily recognized, and the consequences of a failure were relatively easily repaired and non-catastrophic. In today's Navy, none of this is true. Ships and systems have become extremely complex and therefore require a high degree of quality control to assure that the platform conforms to the shipbuilding specification [18].

The American Heritage Dictionary of the English Language defines quality, assurance and control as follows [19]:

> Quality : " A characteristic or attribute of something; a feature, the natural or essential character of something, excellence; superiority, degree or grade of excellence."
>
> Assurance : "The act of assuring, a statement or indication that inspires confidence."
>
> Control : "Authority or ability to regulate, direct, or dominate; a restraining act or influence."

Taking these words one step further, the definition for industrial or contractor quality control could be

CHAPTER 3

SIGNIFICANT REQUIREMENTS OF A GENERAL QUALITY ASSESSMENT PLAN

3.0 OVERVIEW

This chapter is intended to discuss the most significant managerial and technical attributes of a quality assessment plan (QAP) for GRP ship hulls. It is not intended to cover the entire realm of attributes necessary for a complete quality plan. A survey of existing plans has been performed to determine the management attributes. Attributes were selected from each plan and tailored for GRP application. Due to the lack of existing technical attributes, it is proposed that a series of application dependent questions be addressed.

A quality plan developed for any given application consists of general and specific attributes. The general attributes pertain to all GRP ship hull programs while the specific attributes are tailored to a particular program application.

Following a brief introduction to quality control, this chapter elaborates on the significant attributes of a generalized QA plan for GRP structures. Chapter 4 develops the technical attributes for a particular program application by answering the application dependent questions proposed in this chapter.

and thus difficult to model, and (3) deploy when called on and withstand the actual load history for the expected platform life.

sandwich.

4. The compressive modulus of the core and the compressive strength of the facings should be sufficient to prevent wrinkling of the face.

5. The core cells should be small enough to prevent intracell dimpling of the facings.

6. The core should have sufficient compressive strength to resist crushing by design loads acting normal to the panel facings or by compressive stresses induced through flexure.

7. The sandwich material must exhibit adequate overall stiffness to limit local and global hull deflections.

In order to meet the design criteria and thus prevent the sandwich structure from failing in any one of the failure modes, several factors must be determined. Specifically, the design loads must be known and modelled, the structure then must be modelled, a factor of safety assigned and the typical design sequence carried out. In the case of a naval ship hull, the assignment of the factor of safety is not arbitrary. On the contrary, the factor of safety is composed of several elements as indicated in Figure 9 [5]. It is hypothesized, based on the components of the static and dynamic design factors, that the factor of safety could be reduced by some 30-40% by simply improving the level of quality assurance. The key parameter that influences the magnitude of the factor of safety is the performance requirements of the particular platform. In general, the naval ship must be survivable. This means that the ship must [17] : (1) be resistant to underwater shock, (2) resist the operating environment, which is everchanging

illustrated in Figure 7, GRP sandwich designs can have a higher factor of safety for equal structural weight as compared to other shipbuilding materials. The corollary is also true. GRP designs with equal factors of safety can provide a marked reduction in structural weight [5]. As illustrated in Figure 8, hull structural weight is strongly dependent on the factor of safety [3]. In fact, reducing the factor of safety from 7.0 to 3.0 results in a 265 ton or 65% reduction in hull structural weight [3].

Besides possessing an excellent flexural rigidity to weight ratio, the GRP sandwich construction offers other favorable attributes as compared to steel, including [5,16]: (1) reduced hull maintenance costs, (2) fewer transverse frames required thus increasing arrangeable space while reducing labor requirements, (3) adequate shock resistance, (4) competitive production costs, (5) simplified fitting out, (6) double hull safety against water penetration, (7) reduction in thermal and acoustic signatures, and (8) no detectable magnetic signature.

Sandwich structures should be designed to meet the following structural criteria for a given set of design loads [2]:

1. The facings should be thick enough to withstand the tensile, compressive, and shear stresses
2. The core should have sufficient stiffness to withstand the shear stresses.
3. The core should be thick enough and have sufficient shear modulus to prevent overall buckling of the

2.4 GRP STRUCTURAL SANDWICH

The particular type of GRP considered in most of this study is structural sandwich. Structural sandwich consists of three basic elements as shown in Figure 4 [2] : 1) a pair of thin, strong GRP facings; 2) a thick, lightweight core to separate the facings and carry loads from one facing to another; and 3) an adhesive bond which is capable of transmitting shear and axial loads to and from the core. Figure 5 [14] provides a typical bending and shear stress distribution through the sandwich thickness. An analogy can be made to a steel I-beam: the core is the web and the skins are the flanges, while the adhesive is the weld.

The sandwich structure is extremely efficient and is considered an optimum method to use when combining high flexural rigidity and low weight [2,14,15]. As shown in Figure 6 [2], a relative weight increase of 6 percent can yield a 3900 percent increase in relative flexural rigidity as compared to solid GRP. The principle of the I-beam, with savings in weight and optimum strength and stiffness as the main objectives, has been taken a step further with the sandwich concept. Local stresses and impacts applied to one side of a sandwich have a reduced local effect compared to a standard I-beam configuration because the exposed skin and the core distribute the loads into a larger area of the sandwich structure [5,15]. This provides for an extremely efficient structure with respect to stiffness and weight. As

reinforced composites.

Each of the U.S. Navy's GRP quality specifications are either based on small GRP boat technology or are extensions of the research on high performance carbon reinforced composites for aircraft (which is largely on thin laminates). These specifications require a great deal of subjectivity on the part of the QA specialists and incorporate many go-no go tests that may be over-simplified.

The dominant in-process and post-construction method of inspection employed for defect detection in GRP ships is visual inspection with the aid of intense light [5,13]. The use of ultrasonic inspection has for the most part been limited to hull thickness verification [5,13]. In general, the quality of present day GRP naval structures relies mostly on raw material control, sound (but conservative) structural design, and rigid control and implementation of the production method employed [14].

GRP materials present new problems and challenges, both in flaw detection and in assessing the influence of flaw characteristics on performance. Accurate determination of the influence of a given flaw geometry upon strength and stiffness is considerably more difficult than the classical fracture mechanics approach due to the complex damage developed and the multiple failure modes of the GRP material. However, in assessing the performance of GRP, it is reasonable to start by attempting to utilize the methods of fracture mechanics.

2.3 PAST AND PRESENT GRP INSPECTION STANDARDS AND METHODS

The ability to define, implement and maintain quality is considered a major subset of the above factors and a prerequisite for the continued and increased shipboard use of GRP. Improved ability to characterize the quality of the end product will raise confidence and permit reduction of the design factor of safety. The problem is not only one of locating defects, but also developing non-destructive evaluation techniques to determine the effect of defects upon laminate mechanical properties.

The selection of the best nondestructive inspection (NDI) and subsequent nondestructive evaluation (NDE) techniques for a specific application requires detailed knowledge of the application. For example, the required inspection equipment sensitivity, the desired reliability of the application and the cost constraint imposed must be known to effect a proper selection. The NDI techniques used for metals can not be applied to GRP without alteration. Metals have a consistent homogeneous structure which makes detection and evaluation of defects more convenient. In contrast, the structure of GRP is a function of the type of material used, the layup scheme and the layup quality. Composite materials are inherently non-homogeneous and slight variations in the fabrication procedure can produce internal flaws and compromise structural integrity. The development of techniques for detecting such flaws is of increasing concern due to the growing popularity of fiber

program must be tailored to GRP, not a mere clone of the steel program. GRP is not a metal: it is not a homogeneous isotropic material, it cannot be welded, it does not arrive at the construction site from the composite mill in standard plate sizes, but is made on site. GRP does not carry load or fracture in the same manner as does steel; it is an entirely different type of material and it must be treated as such.

GRP could receive undeserving bad publicity unless its introduction into ship hull structures is adequately managed. Design engineers, machinists, and quality assurance specialists must not assume they know GRP based on their knowledge of steel. Even though this material has been used as a hull material by foreign navies, the United States is just beginning to use GRP as the hull structure for high performance naval ships. In effect, the material must undergo the arduous path of material certification and acceptance. As stated by the National Advisory Board, the constraints or factors promoting the use of new materials can be classified under the generic headings of: (1) technical factors, (2) economic factors, (3) contractual factors, and (4) management and organizational factors [12]. Appendix A summarizes the various constraints and promoting factors, and the associated possible solutions or actions for the accelerated utilization of a new material.

The decision made to use GRP should be made based on a weighted comparison of these and other qualitative and quantitative performance aspects of GRP as compared to alternate materials. The attribute weighting is a function of the hull material selection philosophy. Increased use of GRP and other composites should promote new technology and spark innovation, thus advancing automation and improved production methods. These additional improvements make the use of GRP more favorable.

The general use of glass reinforced plastics (GRP) has risen considerably within the last decade and projected trends are favorable as shown in Table 6 [7,8]. The increased GRP usage also applies to marine applications, both structural and non-structural. Glass reinforced plastic materials are currently being used in the construction of minesweeping ships, submarine sonar domes, masts, propeller shaft coverings, protective coverings for wood and steel, storage tanks, pipes of all sizes as well as many other applications.

The structural use of GRP in U.S. naval applications is still in its infancy, not unlike the use of steel a half century ago. Due to initial structural inadequacies, catastrophic failures and other concerns, the U.S. Navy spent extensive resources in the development of a quality assurance program for steels [9,10,11]. It appears that a similar approach must be taken with GRP. It is critical to note, however, that the established quality assurance

currents, (5) higher strength to weight ratio, (6) reduction in ship radiated noise, and (7) reduced hull maintenance [5]. Figure 2 provides a more detailed listing of the advantages of using GRP as a hull structural material.

These improvements are not limited to ships with restricted magnetic signature requirements. Other high performance craft including surface effect ships (SES), submarines, deep submersibles and small waterplane area twin hull (SWATH) ships could further benefit from the reduction of hull structural weight as well as the other advantages. The relative improvement of these ship performance characteristics are a function of the specific GRP design; i.e. sandwich versus mono-skin, relative factors of safety employed and relative hull girder deflections allowed.

Quantitatively, the structural use of GRP compares favorably with conventional shipbuilding materials. Table 3 provides a material property comparison between GRP and other shipbuilding materials [1,2]. Table 4 provides a similar comparison but concentrates on the driving ship performance properties including material acquisition cost, total structural weight, producibility and magnetic signature [3]. Table 5 provides a more detailed cost comparison to emphasize the competitive material and production cost of GRP relative to steel [5]. Figure 3 compares the stress-strain curves of these materials emphasizing the elastic toughness (area under the elastic part of the stress-strain curve) of GRP [6].

reinforced plastic materials with increased structural strength and modulus to weight ratios are predicted. These improved performance qualities of GRP are being explored and implemented by other nations. This is especially true in the various mine warfare ship construction programs as shown in Table 2 [3].

2.2 CHARACTERISTICS OF GRP

Since magnetic mines were first introduced into naval warfare, it has been customary to construct minesweepers and mine countermeasures vessels of non-magnetic materials. In the case of hull structure, the traditional approach has been to use wood construction, generally with heavy multiple-layer planking over laminated transverse framing. The technology of wood construction has not evolved significantly from the early heritage of sailing ships and the traditional techniques are still being used for the construction of wood trawlers and pleasure craft. The use of wood has steadily declined in recent years due to many factors including lower production rates as compared to GRP, the increased shortage of high quality wood and its susceptibility to environmental degradation [4].

Qualitatively, the use of GRP also offers attractive alternatives to steel ships, such as: (1) materials are less energy intensive, (2) reduced construction time allowing for rapid mobilization, (3) reduced overhead and production costs, (4) elimination of magnetic signatures and eddy

CHAPTER 2

BACKGROUND

2.0 OVERVIEW

The development of a quality assessment plan for GRP ship hulls requires knowledge of the materials to be used, applicable inspection standards, available inspection tools and an understanding of the techniques implemented in the past and their relative performance. This chapter will provide the following necessary background information needed to set the stage for the plan development: (1) the status of the reinforced plastics industry, (2) the characteristics of glass reinforced plastics, and (3) the past and present GRP inspection standards and methods employed. Additionally, GRP sandwich structure is briefly addressed and later detailed in Chapter 4.

2.1 STATUS OF GRP INDUSTRY

The use of glass reinforced plastics (GRP) was initially hindered by the relatively high cost of raw materials and slow, expensive processing methods. In the last two decades, the GRP industry has exhibited strong, steady growth due to various reasons. As shown in Table 1 [1], the advantages of use now outweigh the disadvantages for many applications. As reflected in Figure 1 [2], continued significant advances in the development of

CHAPTER 1

INTRODUCTION

This thesis presents the framework for a technical plan for quality assurance of glass reinforced plastic (GRP) used in advanced performance naval ship hulls.

At present, high structural factors of safety dominate glass reinforced plastic (GRP) structural designs and discourage the expansion of GRP use in ship hulls. These are in part a result of the very limited quality assurance procedures used with GRP hulls. It is envisioned that lower factors of safety will be demanded by future weight-limited, high performance ship applications. These anticipated applications provide the motivation for this thesis.

The framework identifies the significant management and technical attributes of a quality assurance plan (QAP). The results of a survey of industry quality assurance plans are used to identify important management attributes. A simplified methodology is developed to aid in identifying the important technical attributes. Once the methodology is defined, several key technical attributes are explored for a specific advanced performance naval ship. The development of the technical attributes constitutes the major thesis effort. Within this effort, the criticality of various defects and their subsequent detection and evaluation are emphasized. Several damage assessment models were analyzed to estimate flaw criticality.

interpreted as "An effective system for integrating the quality-development, quality-maintenance, and quality-improvement effort of the various groups in an organization so as to enable marketing, engineering, production, and service at the most economical levels which allow for full customer satisfaction" [20]. The word quality does not imply best in an absolute sense, but rather best based on the customer's requirements. The words control and assurance represent a management tool used to meet the required quality.

The customer, the U.S.Navy in this case, must demand that the ship, including the hull structure, is built per specification. The U.S.Navy uses the Ship Acquisition Contract Administration Manual (SACAM) for contractual guidance. SACAM states "contractors establish and maintain inspection quality programs which assure that the work required by their contracts conforms to the applicable contract and specifications, and offer to the Government for acceptance only those supplies and services that conform to contractual requirements and, when required, maintain and furnish substantiating objective quality evidence of this conformance" [21].

At present, the quality related documents used by both the contractor and the customer for GRP laminated products consist of (1) NAVSHIPS 250-346-2 INSPECTION MANUAL FOR FIBROUS GLASS REINFORCED PLASTIC LAMINATES , and (2) general and detailed specifications which are contract dependent.

These documents are largely products of the thin GRP boat era. They may place overly restrictive or inadequate requirements on the material. Additionally, emphasis is placed on the use of visual inspection as the significant NDI tool employed to detect defects. The determination of which defects are most critical, which NDI method to use and other important quality related issues are each difficult to make. It is proposed that the technical attributes of a QAP are largely platform and platform mission dependent and can be determined by answering a series of questions. Figure 10 is a function-based flow chart which outlines the basic approach used to determine the generalized attributes.

3.2 DEVELOPMENT OF GENERAL MANAGEMENT ATTRIBUTES

Several quality documents were reviewed for their utility in the formulation of superior management attributes. Quality programs reviewed included: (1) U.S. Air Force Advanced Composites Design Guide [22], (2) U.S.Navy Inspection Manual For Fibrous Glass Reinforced Plastic Laminates NAVSHIPS 250-346-2 [23], (3) Diab-Barracuda AB, Sweden Production Inspection Plan [24], (4) HITCO Quality Inspection Plan [25] and (5) Karlskronavarvet AB, Sweden Inspection Plan GRP-Sandwich number GRP 85-01 [26]. The attributes listed below were taken from the referenced documents and are considered as candidate attributes important to a labor intensive GRP hull construction program.

1. To insure the successful application of GRP structures, it is essential that a quality assurance program be established that considers all aspects of the design and application operations. Figure 11 [22] depicts a typical program that begins with the design interface. Quality assurance must maintain close coordination with the design and production team throughout the design effort. This will help to insure inspectability of the finished product and give the quality control engineer necessary understanding of the structural criteria. The coordination is important. If effective, it will lead to a successful application [22].
2. The QAP must exhibit an effective organization to control the labor intensive, progressively less reversible process [23].
3. The QAP must provide for QA training...not just for the QA department personnel, but for the manufacturing force also. This enables the worker to understand the necessary quality of his or her product [22-26].
4. The QAP must provide for various frequencies and levels of testing. The level and the nature of the test is a function of the timing in the assembly process and the importance of the step [22-26].
5. The most difficult step in the majority of quality processes is controlling the human element. Automation is gradually replacing man in previously labor intensive

processes. These processes exhibit superior quality due to their ability to : (a) continuously monitor, (b) keep records automatically and accurately and (c) be easily altered in case of casualty or change [24].

6. The QAP must be kept simple, easily implemented, tailored to the end product and maintained at the correct level based on product design requirements [20]. A clear statement of the impact that the QA program will have on the total production is necessary. This will keep the QA effort consistent with the overall design approach. The platform design and the production methods employed will drive the degree of quality.
7. Quality control of composite materials requires extra responsibility since the composite laminates are produced on site from various intermediate products. In contrast, metal materials require only mechanical and thermal operations to assemble them into a structure.
8. Three distinct phases of the quality control effort are required; (a) incoming raw materials must be inspected for conformance to material specifications, (b) in-process quality control must be established for conformance to processing specifications during fabrication of the composite material, and (c) as a final check, some combination of destructive and nondestructive testing of the finished structure must be performed. Figure 12 illustrates, in general, the inspection requirements for a composite material [22].

9. The problems caused by the heterogeneity of composite materials in the establishment of realistic quality control standards must be clearly understood. In homogeneous materials, standards can usually be established for the material alone; however, in the case of composite materials, such standards must be related to the specific orientation and intended use of the composite. The only specifications which are likely to be generally applicable are those which refer to methods controlling the production process. All other requirements relating to properties, test methods, test specimen selection, and nondestructive testing must be established for each type of application, with close cooperation between the design, materials, manufacturing, and inspection functions [22].

10. There is a continuing tradeoff between cost, schedule and quality [21]. The ultimate success or failure of an otherwise adequate QA plan can depend on whether it is compromised in efforts to meet the cost or schedule goals. Often the quality issues become a burden as circumstances arise which had not been considered in the original plan development. From a potential buyers viewpoint, the customers must ensure that they are receiving vessels that meet all the specifications of the contract. From the designers point of view, the contractor must define the level of quality that can realistically be achieved. To perform this, the

contractor must identify the tools that are available, or that can be developed, to assure that required level of quality. In all cases, the minimum quality level must be sufficient to avoid obvious blatant construction defects before more elaborate methods are addressed.

Not all of the plans reviewed directly apply to the shipbuilding industry. In fact, Karlskronavarvet AB, Sweden Inspection Plan For GRP-sandwich number GRP 85-01 was the only document reviewed that was prepared exclusively for a labor intensive GRP ship hull production program. Although adequate, this document concentrates on visual inspection as the dominant NDI tool. Karlskronavarvet's quality plan has been included as Appendix B for referral.

The ship hull application is basically different from others in several respects. For example, compared to other products: (1) The performance of a naval combatant ship is not easily measured. For a naval ship, performance is the summation of various parameters including platform acquisition cost, platform life cycle cost, survivability, weight, expected platform life and many others. (2) The environment for hull construction is far from being laboratory clean. (3) The complex and large shape of the hull structure complicates staging requirements and limits cure to room temperature. (4) Due to the thickness requirements of the GRP hull structural sandwich facing, the hull material is opaque and renders visual inspection less

effective. (5) The construction materials used and the large laminating surface create a potentially hazardous styrene-rich layup environment which is awkward to work in and generally employs unskilled, low paid labor. This often leads to less intelligent and less motivated personnel which increases the risk of production defects [1,13].

3.3 THE DETERMINATION OF TECHNICAL ATTRIBUTES

Unlike the management attributes, the technical attributes are products of the particular platform characteristics. They are the backbone of the QAP. Concern is with the quality of advanced naval vehicles constructed of GRP. In order to determine the required technical attributes, it is proposed that a series of questions be developed. These questions, when answered, effectively engineer the QAP to complement the particular platform.

There is no published guide available that lists all the right ingredients and questions that must be addressed when developing a QAP for GRP hull construction. The particular questions proposed were determined by review of the thought sequence and the questions addressed in conventional ship structural designs [27] along with the features of the quality assessment of high performance composites [22]. Figure 13 illustrates the type of questions addressed in a typical advanced composite quality assessment program [22].

To the knowledge of the authors, the plan outlined here

is the first such treatment of this topic. It is proposed that the following questions (Figure 10) be asked and subsequently answered for a specific application in order to determine the important technical attributes of the quality plan. In addition to each question, a corresponding summary of available choices is provided.

Question 1: What are the mission requirements ?

The choices include minehunter, minesweeper, anti-surface warfare, anti-submarine warfare, anti-air warfare, etc. The answer to this question will normally determine the platform requirements.

Question 2: What are the platform requirements ?

The choices include underwater shock resistance, longitudinal bending, maximum hull deflection, acquisition cost, endurance requirements, ballistic protection requirements, magnetic signature requirements, acoustic signature requirements, pressure signature requirements, sprint and endurance ship speeds, etc. The answer to this question will normally determine the important material design parameters.

Question 3: What are the driving material design parameters ?

The choices include interlaminar strength, compressive strength, shear strength, tensile strength, flexural strength, fatigue strength, impact strength, stiffness, material acquisition cost, material production cost, material structural weight, material maintenance requirements, etc.

Question 4: Where are the stress critical areas on the ship ? Certain areas of the ship are critical due to the platform shape, geometry and mission requirements demanded.

The choices include the keel area, the bow, the shell plating below the waterline and the superstructure [17,27].

Question 5: What are the important defects ?

The choices include delaminations, voids, inclusions, uncured resin, improper overall glass to resin ratio, cracks, local omission of layers of glass fiber, discoloration, crazing, blisters, resin starved and rich areas, wrinkles, reinforcement discontinuities, improper thickness, foreign object damage, construction

and assembly defects, etc. Description of each of these defects are well documented [28] and is not detailed here. In addition to the above production process and in-service generated defects, intentionally designed-in features including access holes, various attachments fastened to the face, and hull penetrations need to be addressed. The relative importance of these defects and designed-in features (which may act as flaws) needs to be determined. Chapter 4 performs this in detail based on the the results of a defect survey, damage assessment models and first principles.

Question 6: How can defects prevented ?

The choices include proper supervision, improving the production method, material screening, training of personnel, incorporation of automation to eliminate the man interface in a labor intensive production process, etc [13,14].

Question 7: How can defects detected ? This question is the most difficult to answer and is therefore divided into several sub-questions.

Question 7.1: What are the specification standards that must be met for the given platform ?

Question 7.2: What destructive tests should be used ?

The choices include the evaluation of sample plugs from the hull, the testing of built-in test tabs, and various physical material tests performed on scrap material including hull penetration cutouts. The physical tests include interlaminar shear, flexural strength, tensile strength, void content, resin content, degree of cure, core bond and fatigue [22,26]. In general, the present ASTM test methods are proven for thin laminates, but need to be validated for thick laminates.

Question 7.3: What nondestructive test methods should be used ?

The choices include thermography, acoustic emission, low frequency ultrasonic, impedance mismatch, optical fibers, low energy Xray, visual, sonic coin tapping, holography, proof testing, imbedded strain gages and others [29,30,31]. Table 7 [32] provides a comparison of NDE methods. This comparison includes parameters sensed, flaws detected, types of applications, advantages and disadvantages for each method.

Question 8: How can the test methods be integrated?

The plan recommended for a particular application will depend on the needs of the program. Items that will influence the integration include the defects present and their relative importance, selected inspection methods, standards and specifications, and the proportioning of the QA effort in the stages of construction.

Question 9: How can defects be corrected ?

The choices include the various established methods used by foreign navies and using the results of ongoing research [5,13,14,33]. The defect correction procedures must address permanent repair, replacement and temporary repair.

Question 10: How can defects evaluated ?

The choice includes comparison with various standards. Consideration must be given to ensure that the standards reflect the relative importance of the defects and place the defects in proper platform perspective. The defect location and the methods available for repair should influence the evaluation decision. The ultimate evaluation must determine if the

defect is allowable as is with no waiver needed, needs to be corrected, or is waived based on an engineering assessment.

Question 11: How can the QA effort be proportioned between the various stages of construction ?

The stages include pre-construction, construction and post-construction.

CHAPTER 4

DEVELOPMENT OF SPECIFIC QUALITY ASSESSMENT ATTRIBUTES FOR AN ADVANCED NAVAL VEHICLE

4.0 OVERVIEW

The purpose of this chapter is to apply the general assessment criteria described in Chapter 3 to a specific case. As proposed in Chapter 3, the technical attributes of a quality assessment plan can be developed through answering a series of questions for the particular application. The case that is addressed is an advanced naval vehicle called the Mine Warfare Ship Experimental (MWSX) [3]. The ship is a transversely framed monohull which is weight limited and has a low factor of safety structural design. The hull material is GRP sandwich. The components of the sandwich are woven roving (WR) and chopped strand mat (CSM) faces with isophthallic polyester resin matrix and a high performance polyvinylchloride (PVC) foam core. The mission of the ship is minehunting and mine neutralization. Appendix C contains a design summary of the MWSX [3]. While it is recognized that sophisticated production methods improve quality, this section assumes that the production method is fixed. The assumed production method is semi-automated. The WR/CSM is impregnator dispensed with proper resin content using manual placement and consolidation of plies over a male mold.

using sandwich specimens) are in good agreement with the analytical prediction. This prediction is slightly non-conservative for large delaminations. See Figure 25. Comparing these results with the simple Euler analysis indicates that the Euler prediction is somewhat conservative. It predicts a buckling stress which is lower than both the predicted and observed buckling stress in work done by Chatterjee. The Euler prediction for the identical specimen and delamination geometry used by Chatterjee is plotted on Figure 25. The supporting calculations are shown in Appendix F-4.

Shivakumar and Whitcomb [44] also analyzed a similar problem. Their prediction for a circular delamination in a 2-D quasi-isotropic laminate as (illustrated in Figure 26) indicates that the the actual critical buckling stress may be up to four times higher than that predicted by the simple 1-D Euler approach. The Euler prediction for the identical specimen and delamination geometry used by Shivakumar and Whitcomb is calculated in F-5.

The fact that the Euler approach is conservative is offset somewhat by the actual ship panels possessing a small amount of curvature which acts as eccentricity and reduces the critical buckling stress [27]. Therefore, the Euler approach was used to compare the effect of delaminations to other key defects. Figure 27 depicts delamination length versus per cent compressive failure stress in flexure for instability failure using the Euler

Instability Failure

Another failure mechanism that may govern the allowable size of a delamination is face wrinkling. Face wrinkling is an instability failure which occurs in compression, and is therefore of interest in both global and local loading cases. Figure 23 shows a diagram of instability failure.

The first model is an analysis of a piece of the GRP skin that is distant from the neutral axis (worst case). It shows that a delamination of approximately 14 inches is allowable before the face will buckle away from the core. This analysis is based on the maximum stress developed from a once in 20 years maximum bending moment load and follows Euler buckling theory. It assumes that the delamination is rectangular (through the width) and the core acts only as simple supports to the face at the edge of the delamination. The details of this analysis are provided in Appendix F-3.

Chatterjee et. al. [43] performed a more sophisticated analysis of the same phenomenon. The sandwich skin was modelled as an assemblage of four beam elements (shown in Figure 24). The differential equations governing the deformations of the beam (including shear deformations) were solved and the stiffness matrices derived. The analytical prediction turns out to be very similar to the Euler stress vs. column slenderness ratio curves [43]. The experimental results (which were obtained

any delamination greater than 0.65 inches. As the delamination size increases, the laminate will fail at a decreasing percent of the flexural failure stress. See Appendix F-7 for supporting calculations.

The limitations of this model include:

(1) It is assumed that the delamination will propagate collinearly (Mode II) along the interface between plies. This is shown to be the case for the GR/EP beams of the dimensions discussed, but has not been demonstrated for WR/CSM in polyester.

(2) The core material and the core-skin interface are considered by using a solid beam analogy. It is assumed that the delamination was in the laminated face. Figure 18 shows a suggested method of arranging the beam elements so the analysis could be rederived to model a delamination in the core-skin interface.

The second model evaluated for potential use was by Whitcomb [42]. His analysis is adaptable to a sandwich configuration, but requires a finite element approach to obtain the unit load solutions for the desired laminate type. The development is based on normalized solution values and has the ability to account for both mechanical and thermal loads as well as Mode I, Mode II or mixed Mode (I and II) propagation. This model was not used because the effort required was not consistent with the scope of this thesis.

The 8 ft. element was evaluated under a local loading condition (for example, a uniform pressure simulating wave slamming or shock). For this loading, the panel would be in flexure with the maximum moment at mid span. A delamination in the skin-core interface at mid span is located near the fixed end at mid-thickness (worst case) of the 4 ft. model beam. The model for local loading is shown in Figure 20.

The 90 ft. element was evaluated based on a once in 20 years estimated maximum bending moment loading. This global loading places the entire element in uniform compression (or tension). It is assumed that the keel is sufficiently thick so that shear stresses (similar to those of a beam in pure flexure with a maximum face stress equal to the uniform stress of the actual keel, 2970 psi) would develop under this flexural. A delamination in the lower skin-core interface at mid span in the actual 90 ft. keel element was modelled as a delamination proportionately the same distance away from the neutral axis, located near the fixed end in a 45 ft. beam. See Figure 21.

The results shown in Figure 22 indicate that the global loading case is rather insensitive to the presence of a delamination, requiring a length of 59 inches for failure. However, the local bending case revealed that the panel will fail by catastrophic delamination propagation before flexural failure for

fracture mechanics approach (Griffith's criteria) which states that the loss in the total strain energy due to an incremental change in the crack length is equal to the surface fracture energy that is necessary to create the corresponding surface area [41].

This development, summarized in Appendix F-1, shows that the critical value of the tip load is a function of location and length of delamination, material properties, geometry, and surface fracture energy for the given matrix-fiber combination.

The solution, though complicated, is general enough to be used for a beam made of any material in a wide variety of dimensions. The configuration of the beam elements precludes adapting this model directly to a sandwich beam. Figure 18 shows a proposed configuration for possible future studies of sandwich beams.

In the absence of a direct solution for the sandwich construction, a solid beam analogy was developed. The solid beam is dimensioned to have the same flexural stiffness as the sandwich in the area below the waterline of the MWSX. The dimensions are derived in Appendix F-2. Using this equivalency, the following cases were evaluated:

A. 8 ft. element far from the ship neutral axis representing a characteristic 8 ft. x 8 ft. unsupported span
B. 90 ft. element representing the thick keel

Figure 19 depicts these cases.

4.1.2 DELAMINATION MODEL EVALUATION

To evaluate the criticality of a delamination flaw, five existing models were examined and adapted to the MWSX advanced naval platform.

Two of the models consider the shear propagation of a delamination. The other three models consider a buckling instability failure caused by delamination. Only two models were originally derived for sandwich construction, while the others have been adapted by approximate analogy methods to estimate their general significance.

Shear Propagation of Delaminations

The first model by Ramkumar et. al. [40] formulates a closed form solution for the static failure analysis of a graphite/epoxy (GR/EP, AS/3501) beam with a full width delamination at any axial location between any two laminae. The beam used is cantilevered and tip loaded with a uniform cross section.

This model analyzes the delaminated beam as four separate beam elements joined together at the crack tips with the appropriate boundary conditions. Figure 17 shows the model configuration. Shear deformation effects are incorporated by treating each beam element as a Timoshenko beam, and the total strain energy is obtained using Clapeyron's theorem. The criticality of the delamination is determined by using a classical

Wright. Micrographs of these samples clearly show substantially more than 4% void content (but the voids are concentrated in mid-thickness region).

The effect of voids on compressive strength is very similar to the effect on ILSS. For void contents from 0.5 to 6%, compressive strength exhibits a generally linear decrease of approximately 6% for each 1% increase in void content [37]. Another model by Foye shows a non-linear fit which , as with ILSS, is also representative of the data [39]. Appendix E-2 adapts Foye's model to predict the trend of compressive strength degradation in GRP due to voids. The results, shown in Figure 15, indicate a leveling off of compressive strength for void contents above approximately 3.5%. This result is slightly less conservative than the linear prediction.

Based on the reduced effect of voids observed by Cable and Thomas, Foye's model was chosen as representative of the effect of voids on compressive strength and subsequently used to compare the effect of voids with the effect of other defects. Figure 16 shows the prediction of this model normalized to the compressive failure stress in flexure. A void content of 4% reduces the flexural strength in the compression mode by 26%.

content of 4% [35]. The decrease was approximately linear and the results were valid regardless of the type of resin or the type of fiber. By viewing voids as small cracks, Corten [37] used a fracture mechanics analysis to quantify the effect of voids on ILSS. By assuming that an equivalent crack length is proportional to the cube root of the void content, a non-linear fit of similar data was made (see Appendix E-1).

Figure 14 shows how both approaches provide good representations of the data. However, the fracture mechanics approach indicates a leveling off of ILSS for void contents greater than 3%. Thus, the broad based analysis by Judd and Wright may be conservative. Research by Cable and Thomas [38] supports this. Their work, which is part of a larger ongoing effort in this area at MIT, is included in Appendix D. Their results indicate that voids, intentionally induced in thin graphite epoxy laminates, had a much smaller effect on ILSS than predicted by either of the previously mentioned studies. For the specimens with the most severe porosity, no degradation in ILSS was observed using a maximum load failure criterion. Based on a first significant reduction in modulus failure criterion, a 30% reduction in ILSS was reported. This degradation corresponds to a void content of approximately 4% based on the prediction of Judd and

generally two types of voids: (1) voids along individual fibers (void diameter related to fiber spacing and typically between 5-20 micro meters) and (2) voids between laminae and in resin rich pockets [35].

A standard test to measure void content is available in ASTM D2734-70. The void content can be determined from the weight of the fibers and the weight of the resin in a known weight of composite material. The accuracy of this test is reported to vary from ± 0.5% [35] to ± 1.6% [36] due to the reliability of density measurements. The void content is usually expressed as a fraction of the total volume. The total volume is made up of resin and fibers while the remainder is called voids, or sometimes porosity.

Voids can be caused by incomplete wetting out or improper ply consolidation. This leads to the entrapment of air. Another cause of voids is the entrapment of volatiles produced during the cure cycle of the resin. These can be residual solvents or products of the resin chemical reaction which volatize as a result of the increased temperature associated with the exotherm [35].

The effect of voids on ILSS has been studied. From an evaluation of a large data base, Judd and Wright concluded that the ILSS of composite materials decreases 7% for each 1% of voids up to a total void

that predict performance degradation of composite laminates as a function of defect type and location were evaluated. These models address individual defects independently and not interactions between different defects.

Paragraphs 4.1.1 through 4.1.4 describe the particular models addressed. The model assumptions, limitations, findings and recommendations are provided. Details of model development including calculations are contained in the corresponding appendices.

The level of detail contained in the following paragraphs is greater than in the answers to the earlier questions. This is consistent with the complexity and relative importance of assessing flaw criticality in the development of a GRP quality program.

4.1.1 VOID MODEL EVALUATION

This section examines the effects of voids on interlaminar shear strength (ILSS) and compressive strength. Voids are defined and discussed, then analytical and empirical models which predict the effects of voids are examined. The model used in comparing the effects of voids to the effects of other defects is described, and results are provided.

Besides the large cavities that may occur as a result of gross manufacturing errors, there are

Question 3 can be classified as either Type A or Type B. Type A are gross defects including such items as large inclusions, improper glass to resin ratio, omission of reinforcement plies, and blatant errors in the production process such as a glove left in the laminate. Type B defects are more subtle, but can be equally severe. They include voids, delaminations, blisters, reinforcement discontinuities, holes, notches, stress concentrations due to hull cutouts, discoloration from excessive exotherm or water damage, resin starved and rich areas, wrinkles, uncured resin, cracks, and foreign object damage.

These defects can occur during the hull manufacturing process. Type A defects are extremely important. Even though they are generally controllable, their absence must be assured. Type B defects are generally less controllable and will be the focus of this section.

Based on the important material design parameters obtained from Question 3 and the Type B defects listed here, voids, delaminations, reinforcement discontinuities, holes, and notches are considered the most limiting defects jeopardizing quality, and were chosen for further evaluation. These defects are considered to be the most common and have the most potential for degradation [3,5,14,28,34]. In order to estimate the effect of these defects, several models

shear strength to resist shock loading, (3) skin stiffness to resist shell buckling and limit panel deflections, (4) fracture toughness to resist flaw propagation and impact loading and (5) laminate compressive strength to resist longitudinal bending and panel buckling [3,5]. Several other design parameters including cost and producibility play equally important roles, but were not considered here because the hull materials used and production method employed were assumed fixed. Reference [3] performs the detailed hull material selection and structural design based on these additional parameters.

Question 4: Where are the stress critical areas on the ship ?

Based on the structural design of the MWSX [3] and past naval ship designs [27], the stress critical areas on the hull include (in order of importance): (1) the keel area due to underwater shock, longitudinal bending and groundings, (2) the bow due to wave slamming and mooring accidents, and (3) the shell plating below the waterline due to shock and various impacts.

Question 5: What are the important defects ?

The defects that affect the design parameters from

environmental conditions. Appendix C and Reference [3] provide additional mission related requirements.

Question 2: What are the platform requirements ?

Based on the platform mission, the performance requirements that drive the structural design include, in order of importance: underwater shock, shell buckling, impact by wave slamming, hull girder and panel deflections, and longitudinal bending [3]. In general, the performance requirements were a function of hull geometry and location. The underwater shock requirement drove the design of the hull below the waterline [3]. Underwater shock can cause failure by shear yield of the PVC core [5], or by producing and propagating skin or skin-core interface delaminations. There are no ballistic protection requirements for this design.

Question 3: What are the driving material design parameters ?

Based on the driving performance requirements, the material design parameters that are most important in this particular design include adequate values of: (1) interlaminar shear strength of the skin and the skin-core interface to resist delaminations, (2) core

4.1 ASSESSMENT OF TECHNICAL ATTRIBUTES

With the project and production method fixed, the proposed Questions 1 through 11 need to be answered and recommendations made as to the technical aspects of the quality assessment program. The criteria contained in Chapter 3 consist of a series of platform dependent questions where the answer to each question depends on the answer to the preceding questions. Questions 1 through 4 are important, but are briefly answered. They serve to set the stage to answer the more interesting questions. The answers to these initial questions are based on previous design experience [5,13,16] and available test data. Each of the questions proposed in Section 3.3 will be answered, but the majority of the effort will be applied to Question 5 (defect importance), Question 7 (defect detection) and Question 10 (defect evaluation).

Question 1: What are the mission requirements ?

The mission of the selected platform is that of a minehunter and minesweeper. The ship must be capable of detecting and neutralizing surfaced and submerged pressure sensitive, acoustically-triggered and magnetic mines. The ship must be capable of operating independently while performing its mission in various

approach. It is interesting to note that a delamination smaller than 5.45 inches does not reduce the failure stress. See Appendix F-6 for supporting calculations.

Summary

The results of this Section are summarized in Table 8. For the global loading case, the instability failure will occur first. For the local loading case, shear propagation of a delamination is the estimated failure mode.

Delamination has been shown to be a an important defect that deserves added attention during design and construction for proper quality assurance.

4.1.3 STRESS CONCENTRATION MODEL EVALUATIONS

Based on the MWSX design, (subject to a once in 20 years bending moment load) the effects of holes (with and without cracks) in 8 ft. x 8ft. panels located far from the ship neutral axis were examined. The characteristic unsupported span dimension on the MWSX. This loading produces a maximum stress of 2970 psi as illustrated in Figure 28.

The effect of anisotropy on the stress concentration for a hole in an infinite plate (constructed of WR/CSM in polyester resin which is the typical naval GRP ship hull material) was calculated [45] to be 3.9. This is 1.3 times larger than the isotropic value of 3.0. See Appendix G-1 for calculations. Thus, it can be stated that the presence

of a hole can cause this material to fail at a stress that is approximately 25% of the face failure stress in flexure.

Ships typically have many penetrations throughout the structure for access, piping and wiring runs, etc. These openings are cut out of the finished laminate and can range in size from a 1 inch hole in the shell for an overboard discharge to a 5 ft. X 10 ft. or larger opening in the main deck for equipment removal. Many of the smaller holes are not reinforced [14].

Using Neuber's nomograph [46], stress concentrations for holes in an 8 ft. x 8 ft. panel were determined. Figure 29 shows the geometry evaluated. The results are shown in Table 9. Assuming the material is isotropic, the limiting hole (compression failure) was approximately 6 ft. in diameter. An estimate for the limiting diameter in the orthotropic case was calculated using the correction factor ($K_I$ortho / $K_I$iso = 1.3) to be 62 inches. The loading in both these cases was a once in 20 years maximum bending moment and associated 2970 psi maximum stress.

It is reasonable to assume that the penetrations through the hull will not be totally crack free. To assess this effect, a fracture mechanics analysis was performed on a hole with cracks as shown in Figure 30. Various combinations of hole diameters and crack lengths produce failure in 8 ft. x 8 ft. plates far from the ship neutral axis. In this case, failure is defined to occur when the

predicted stress intensity factor (K_I) is greater than or equal to the candidate opening mode critical stress intensity factor (K_Q). A value of 14 ksi-(inch)$^{1/2}$ is used for K_Q [47] and K_I is obtained from Reference 48. The calculations are shown in Appendix G-2. The correction factor of 1.3 is used to estimate the orthotropic condition. The results shown in Table 10 indicate a strong and increasing sensitivity to small cracks as the hole diameter increases. Figure 31 shows crack length versus per cent compressive failure stress in flexure for a crack only. The calculations are contained in Appendix G-3.

The results of this Section show that a hole with cracks is an extremely important defect. Even at loads less than a once in 20 years worst case, the effect of this defect cannot be overlooked. For example, at half the worst case load, which could occur routinely, a 12 inch diameter hole with two 6 inch cracks would cause failure if the hole was in the main deck or low in the shell. The effects of fatigue could also propagate the cracks at K_I values as low as 20 to 30 percent of K_Q [49].

4.1.4 DISCONTINUITY MODEL EVALUATION

This section evaluates the effect of ply gaps and ply overlaps on laminate properties.

When laying up WR/CSM on a ship hull,the decision on how to place successive plies must be made. Figure 32 illustrates the following options:

1. Butted edges, not staggered

2. Butted edges, staggered

3. Overlapped edges, not staggered

4. overlapped edges, staggered

Recent practice for military ships is to use Option #2 [50].

Associated with ply placement are the special constraints imposed by the exotherm during resin cure. The total number of plies that can be laid wet on wet is limited. This limit could be reached in a single shift using current production methods. As a result, the next production session would lay wet plies on partially or fully cured plies.

Owens Corning Fiberglass [51] has compared laminates constructed with staggered, butted edges versus continuous ply laminates. The discontinuous laminates were laid up half at a time with a single day delay. See Figure 33. This method of layup simulates realistic production procedures. The results of mechanical testing of these laminates are shown in Table 11. The trend exhibits a small decrease in properties in the 0 degree direction and a slight increase in the 90 degree properties. Therefore, a properly staggered, butted edge layup does not significantly degrade the laminate performance.

The effect of not staggering the location of ply edges can be approximated by assuming that the discontinuous plies do not contribute to the strength of the laminate. Thus, a 6 ply system with discontinuities in

the 4 interior plies will theoretically have 33% (2 effective plies of 6) of the continuous strength. Fukada and Kuwata [52] observed a decrease to 37.5% of continuous strength in experiments conducted on a glass cloth reinforced polyester laminate. This demonstrates that the decision to stagger ply edges is correct.

The decision to overlap or butt ply edges is not as clear. The Owens Corning Fiberglass data is based on ply edge butts constructed in laboratory conditions. In a laboratory environment, nearly perfect butts between ply edges can be achieved. In contrast, actual production specifications allow ply edge gaps of some small dimension [23,24].

It is reasonable to assume that the reduction in strength is caused by two separate effects: (1) stress concentration due solely to the presence of the discontinuity, and (2) stress concentration due to an overlap or gap in the ply edges. There is evidence that shows in the case of overlapping ply edges, the longer the overlap the better. Freed [53] determined that a sufficiently long overlap effectively eliminates the stress concentration due to the overlap, as long as they are staggered. The improvement in strength diminished beyond a 1/2 inch overlap.

Similarly, gaps between plies can be expected to reduce the laminate strength. As the ply edge gap approaches a perfect butt, the stress concentration due to

the gap is effectively eliminated.

It is anticipated that both ply overlaps and ply gaps will: (1) cause small amounts of local eccentricity (which could be important in buckling), (2) not cause any laminate thickness deviation (since staggered overlaps or gaps will be averaged out over the thicknesses of interest), and (3) create small resin rich areas (which can be important to laminate failure via matrix crack initiation).

Neither option, overlapping or butting ply edges, stands out as a clear cut choice based on these aspects of performance. But, as long as the gaps or overlaps are staggered through the thickness, a small effect is estimated.

4.1.5 SUMMARY OF MODELS

Sections 4.1.1 through 4.1.4 reviewed several defect types in order to determine their relative importance. The defects studied included voids, delaminations, holes with and without cracks, and ply discontinuities. In order to place these defects in the proper perspective the following summary is provided.

Table 12 summarizes the results of the models evaluated. Ply gaps and ply overlaps are not included because their effect is small compared to the other defects.

The two loading cases that were used to evaluate the effect of key defects are:

1. Global bending of the entire hull girder, based on a once in 20 years estimate of the worst bending moment.

2. Local bending, due to a distributed pressure load, simulating wave slamming or shock.

The results clearly show that voids at reasonable contents of 5-10% are not the same order of magnitude problem as compared to the other defects.

Section 4.1.2 stated that delaminations were important defects, but do they occur in marine applications ? As an example to show that they can occur, Japanese fishing boats have experienced extremely large delaminations from wave slamming [54]. Extensive delamination occurred in outer shells from bilge to topside while the vessel operated in rough winter seas. The delaminations were 2 to 6 plies deep and up to seven square meters in area. There were no catastrophic failures in this case, but these vessels were double hulled. Even though they were taken out of service for major repairs, this experience is a good example of the damage tolerance of GRP hulls.

Section 4.1.3 demonstrated that the effects of hull penetrations are strongly sensitive to the presence of small cracks. Modelling these penetrations as circular holes is not considered conservative. Related research [55] showed that circular cutouts are actually worse than square or rectangular shaped cutouts with rounded radii. This is a classic example

of how GRP is so very different from steel. In steel, circular cutouts are better (lower stress concentration factor), but in GRP the failure mode must be considered. Circular cutouts only develop two damage areas. The other shapes develop four damage areas (one at each corner) which relaxes local stresses and absorbs more energy.

The results for each defect considered are based on a static analysis only. The effect of fatigue in propagating the defect was not considered. It has been demonstrated that fatigue could propagate cracks at K_I values as low as 20-30 % of K_Q [49].

A static uniform pressure was used to model the more complicated shock and wave slamming loads. It is reported [14] that shear yield of the PVC core is the dominant failure mode in shock. Shock was not analyzed in this study, but our results indicate that the presence of defects may alter the failure mode.

Bow slamming is a more frequent loading as compared to shock from under water explosion. It is standard design practice to use a uniform pressure to model slamming loads [14]. A typical design value for this load is 28 psi [14]. This number includes the total factor of safety as contained in Figure 9. Slamming pressures elsewhere on the hull can be expected to be lower (approximately 7 psi). The complex geometry of the bow area was not analyzed in this

study. Our results indicate that delaminations and cracks in hull penetrations may propagate even at the lower slamming pressures experienced in the keel and areas of the shell other than the bow.

Question 6: How can defects prevented ?

The controls enforced to limit the types of defects evaluated in answering Question 5 include: (1) adequate supervision during the hull production process, (2) training and certification of all production related personnel, and (3) increased use of in-process inspection to detect the defect and make corrections prior to material cure. Another option to consider is to limit the production of defects by improving the production method employed. The production method is assumed fixed in this thesis, but changes that could be exercised include: (1) incorporation of automation in the form of mechanical impregnators and robotics to reduce the human interface, (2) use of an autoclave to cure structural components that require improved strength, and (3) use of prefabrication to produce flatwork and other common shapes including frames. Each of these options, especially prefabrication, provide the potential for increased production rates while improving product quality [56].

An example of an innovative production related idea

to aid in the prevention of defects is illustrated in Figure 34. This instrumented roller could provide the hull material consolidation process additional consistency. The idea for this roller was developed by the authors. The instrumented tool could be used to consolidate plies during layup while providing the worker in-process feedback as to the roller forces applied. This could allow for immediate application pressure changes, if necessary, and improve the repeatibility of the layup.

Question 7: How can defects be detected ?

In order to detect defects several conditions must be met. Assuming that a defect candidate exists, the defect must first be detected with some form of NDI. Once detected, the results of the NDI must be compared to existing standards to evaluate the effect of the defect. If the defect exceeds that allowed by the standards, then the question of what to do about the defect must be resolved. The standards which are required must be consistent with the material design parameters as described in paragraph 4.1.3. This suggests that the standards be platform dependent so as not to enforce either unnecessary or overly restrictive standards on the platform. Additionally, specification standards established during the thin GRP boat hull era should not be blindly enforced. In effect, the standards enforced

should be consistent with the particular project philosophy and must meet the required material design parameters. The answers to the following three sub-questions provide a review of current U.S.Navy standards, recommend destructive and nondestructive test methods, respectively.

Question 7.1: What are the specification standards that must be met for the given platform ?

The intent of this section is to examine several important standards currently used by the U.S.Navy. Based on the previously developed estimates of the effect of defects, (as contained in Sections 4.1.1 through 4.1.5) the corresponding standards will be placed in perspective.

The following standards are based largely on the Inspection Manual For Fibrous Glass Reinforced Plastic Laminates [23].

Voids

A. The void content will be less than 4%.
B. There will not be any areas of unreinforced resin greater than 1/16 inch in thickness.
C. No voids are allowed to extend through more than one ply.
D. There shall not be any voids more than 1/2 inch in their greatest dimension.
E. Only 1 void, 1/8 to 1/2 inch in its greatest dimension, is allowed in any 6 in. x 6 in. area (regardless of what the thickness is).
F. Up to 3 voids per ply (that are 1/8 to 1/2 inch in their greatest dimension) are allowed in any 12 in. x 12 in. area, not to exceed 20 voids. For example, a 6 ply system is allowed to have 18 1/2 inch voids (6 x

3 = 18) in any 12 in. x 12 in. area, but a 7 ply system is limited to 20 1/2 inch voids (7 x 3 = 21 but limit is 20).

Delaminations

A. There shall be no areas of delamination.

Ply Gaps

A. Seams of adjacent piles of reinforcement shall not overlap more than 1/2 inch or gap more than 1/8 inch.
B. Seams shall be staggered not less than 6 inches.

Holes

A. Penetrations will be circular if possible.
B. When circular is not practical, rounded radii greater than 1/8 th of the dimension normal to the direction of principal stress will be used.

Based on the amount of guidance given, voids appear to be very important. But, since absolutely no delaminations are allowed, perhaps delaminations are more critical than voids. The technical evaluation of the effect of defects in Paragraph 4.1.1 through 4.1.5 provides a basis for comparison. For example, a 6% void content was shown to be equivalent to a:

7.0 inch delamination based on instability failure. See Figure 27.

1.5 inch delamination based on shear propagation under local bending. See Figure 22.

0.5 inch crack based on fracture mechanics. See Figure 31.

6.0 inch diameter hole with two small cracks less than 1/8 inch long based on fracture mechanics. See Table 10.

This equivalency is the basis for the following critical evaluation of the standards:

A. The presence of cracks in the edges of penetrations was not mentioned in the inspection manual. This is a crucial oversight. A 6 inch diameter hole with two small cracks is estimated to be equivalent in effect to a level of void content that is unacceptable (greater than 4%), it is clear that guidance concerning the presence of cracks in hole edges should be included.

B. The 1/2 inch limit on void size seems overly conservative. What these standards call a 1/2 inch void is similar to what is called a delamination in this thesis. The delamination is through the width and is therefore more severe than a void of the same dimension. Yet, a 1/2 inch delamination is estimated to have a negligible effect. See Figure 22. Based on this estimate, a larger void size could possibly be allowed. The effect of a single 3/4 inch void (for example) is less than the effect of other allowable defects.

C. Since the effect of more than a single void was not estimated, the standards for multiple voids will not be quantitatively addressed. They do not appear to be overly conservative.

D. The standard for ply seam gap or overlap is not in total agreement with the previous estimate of the effect of these defects. It does call for gaps or overlaps to be staggered through the thickness which

agrees with this estimate. Also, the specified limit on the ply gap is correctly stated. The estimate of the effect of gaps does indicate that the gap be as small as possible. However, the standard specifies the limits on the size of the overlap exactly opposite the way it should. For example, based on the estimated effect, the overlap should be at least 1/2 inch, not up to a 1/2 inch.

It is appropriate to comment on the history of some of these standards. The inspection manual [23] went into effect in 1964. The references listed in the bibliography of this manual date from 1935 to 1961, and the average date is 1955. These standards were established when the only important GRP structures the U.S.Navy was building were small boats (typically 26 feet long). This application, though important, is orders of magnitude less demanding than the hull of an advanced naval platform. Additionally, less was known about GRP in 1964 than is known today. The result is that these standards are based mainly on workmanship considerations, as opposed to a technical evaluation of the effect of the defect. This is reported to be the case for delaminations [57]. Production experience showed that good workmanship results in a laminate with no delaminations, therefore no delaminations were allowed. There is nothing inappropriate with basing a standard on what is known to be the attainable level of

the proposed test arrangement. Finished GRP ship hulls are currently being raised, moved out, and placed into the water using cranes [14], so this technique is proven. If the AE system indicates any damage during the proof test, ultrasonic transmission devices could be used to further locate and define the damage.

The use of AE for continuous monitoring is a bold proposal, but not without precedent. In fact, successful in-flight acoustic emission monitoring aboard a test aircraft [72] indicates that AE monitoring is feasible in military applications and in high noise, high electronic interference environments. A major advantage of using AE is that the ship does not have to be drydocked to gain information on the condition of the hull. In the event that AE indicates serious damage, the ship would be taken out of service or placed on restricted operations until the problem can be corrected. Repair of the hull below the waterline will require drydocking. When the ship is drydocked, ultrasonics can be used to further define the damage that was initially detected by AE.

Question 9: How can defects be corrected ?

Ideally, the best method to correct defects is to eliminate or reduce their production as described in answering Question 6. In practice, once a potential defect

both Type A and B defects.

Proof testing of a ship hull is a challenging task. The idea of using a pre-service test to demonstrate quality and the ability of a hull to withstand a loading more severe than the anticipated in-service loading is not totally new to shipbuilding, however. The Japanese have performed actual bending tests on completed GRP hulls [70]. Based on a 1968 standard, this test is required to be performed on fishing vessels over 60 tons in displacement. As of 1973, over 30 ships had been tested. The test consists of supporting the hull at two points and applying a bending moment equal to the displacement times the length divided by 20. This represents an estimate of the maximum hogging or sagging moment at sea. Similar testing has been performed as early as 1919 and with U.S.Navy destroyers in 1931 [71].

It is proposed that a bending proof test be performed on the prototype GRP hull of the advanced naval vehicle. This test could be instrumented with AE sensors and serve to produce the baseline AE signature for that hull. If affordable, the hull or components could be taken all the way to failure, in order to correlate AE signals or counts with failure initiation. Elaborate testing machines are not required. It is envisioned that 4 cranes could provide the two point support system, and a series of distributed weights within the hull or on the main deck could provide the required bending moment. Figure 38 shows a diagram of

Pre-construction

A. Use of material screening was not addressed, but would continue to be a crucial part of the overall quality control method.

During-construction:

A. Build in a test tab of extra material for destructive testing.
B. Use a low resolution, high speed sonic technique equivalent to automated coin tapping.
C. Visual

Pre-service: (prototype hull only)

A. Use a proof test on the prototype hull with acoustic emission monitoring and high resolution ultrasonic transmission and visual follow up.

Post-construction: (for all ship hulls)

A. Use of acoustic emission as a continuous, in-service, global monitoring technique.
B. Use of ultrasonic transmission as a local monitoring technique to follow up on indications of damage from the AE monitoring system, and to thoroughly examine critical locations of the hull.
C. Visual

The test tabs would come from non-critical areas just above the top of the shell (see Figure 35). By running the standard series of ASTM tests, a worthwhile (but by no means all-inclusive) verification of basic properties can be made before the hull is completed. This will allow any discrepancies to be evaluated and corrected (if necessary) without having to reject a finished product.

The automated sonic technique provides a more scientific approach to what is already done in practice: manual coin tapping. As the hull is being laid up, this high speed method could be employed for rapid location of

effort could prove beneficial in providing an affordable, global means of damage assessment.

The second promising testing technique is the use of strain gages imbedded in the core and laminate of the hull material. This test method is field proven and is currently used on the Swedish Landsort class minehunter. As with the optical fiber system, the strain gages are distributed in the area of interest and supported by a central signal processor. The knowledge of the actual strain in the core is extremely useful as it can provide direct information about the condition of the laminate. The reason this method was not selected was that the current procedures for installing these strain gages may create limiting defects. They are installed by cutting a plug out of the laminate, and replacing it with a strain gage in a plug of epoxy. As discussed in paragraph 4.1.3, the presence of a hole, especially if cracks are introduced at the edge, is a potentially critical defect.

Ideally, we would like to combine the best features of each method to form the local and global inspection plan. The answer to Question 8 performs this in detail.

Question 8: How can the detection methods be integrated?

The integrated detection plan is listed and later described in more detail.

in-service monitoring [68,69]. One method evaluated uses optical quality fibers that have a strain to fail similar to or slightly less than woven roving reinforcement. These fibers are envisioned to be an integral part of the GRP skin, and would be layed up at the same time as the rest of the hull laminate. It is possible that the material could be purchased this way (combination WR/CSM with continuous optical quality fibers in one direction, spaced approximately 6 inch apart). By laying up one continuous width of this material from deck edge to deck edge, and adding a series of optical fibers similarly spaced in the longitudinal direction, (see Figure 37) the finished laminate would provide a 3-D grid of optical fibers. This grid must be attached to a light source and processing system. Once in place, the most basic information available using this grid would be a simple go-no-go signal. That is, if the optical fiber breaks, the interruption in the transmission of light is sensed and recorded. If multiple fibers break, an accurate fix on the location of the damage may be possible. The reasons this system was not chosen are: (1) there are no examples of successful field applications that perform continuous in-service monitoring (to the knowledge of the authors), and (2) the extensive research and development effort required to place such a detection system in service is not consistent with the NDT selection criteria described above. It is the opinion of the authors that such an

are such good transmitters of stress waves. Certain types of interference (like EMI and RFI) can not be entirely eliminated, but can be filtered to an acceptable level in most cases.

(h) Recent advances in micro-processor technology make complex analysis techniques fast and simple to use.

(i) Instruments designed for use by inspectors (not lab engineers) already exist for FRP.

(j) A secondary benefit of AE technology may be a better understanding of failure mechanisms, and other uses as a design tool, not just a quality control tool. Because AE is a sensitive method of detecting the onset of laminate microcracking, it may be well suited for defining a design strain allowable.

Other NDT Methods

The other NDT methods recommended for use were visual inspection, ultrasonic inspection, and proof testing. The method description, mechanism of operation, and the advantages and disadvantages of use associated with each of these methods will not discussed here. Additional information can be obtained from References 28-32,62,and 64. The major methods attained from the review of these references include: (1) the use of an automated sonic coin tap for global identification of defects, (2) the use of low frequency ultrasonic inspection for local definition of defects, and (3) the use of a ship hull bending proof test to certify the hull structure.

There are two additional testing techniques that were not chosen for use that deserve to be addressed based on their promise for shipboard use.

The first is the use of optical fibers for continuous

the structural integrity of cherry picker booms used by power companies when working on elevated electrical equipment. The booms are fitted out with AE sensors and loaded to three times the rated working load. If there are no indications of serious damage, the booms are considered fit for further use. The interval for this test is annually, or sooner if there are any indications of problems or misuse. The result has been "enormous savings as well as increased safety" and the testing is "cheap and quick" [63].

Advantages of using AE include [62]:

(a) It has developed into a reliable quality control tool in the chemical process industry for both metals and FRP.

(b) It allows material to be tested in-service, and in many cases, on-line. As a result, more frequent or even continuous monitoring is practical.

(c) It provides information about the entire item, not just a small local area. Therefore it is very complimentary to other non-destructive techniques which provide localized resolution.

(d) The sensitivity is sufficient to act as an early warning of defect growth before it becomes serious.

(e) Compared to other NDT methods, AE has predetermined,objective evaluation criteria and is not open to the subjectivity of the operator's interpretation.

(f) The growth of AE testing has been extraordinary in the last 5 years and it is anticipated that the use of permanent on-line monitors will show similar growth, evolving into a relatively low cost standard component in chemical plant control rooms.

(g) Background noise can be virtually eliminated. GRP is better than steel in this area because metals

or, more importantly to this paper, the presence of defects in the laminate (voids, delaminations, and holes).

An acoustic emission sensor is a device that generates an electrical signal when it is stimulated by an acoustic wave. Most materials exhibit acoustic emission over a wide range of frequencies and different acoustic modes so that the choice of a sensor is usually not critical [61].

The majority of acoustic emission sensors are piezoelectric [61]. The acoustic emission electrical signal is as complex and has the same random character as the AE which led to that signal. Thus, the signal will have many characteristics which can be evaluated. Perhaps the simplest and most useful method of signal analysis is the AE count [61]. An AE count is simply the number of times the acoustic emission waveform crosses the threshold of detection during a burst of acoustic energy, as shown in Figure 36.

AE has been demonstrated to be an important, reliable non-destructive tool in several established applications.

Fowler [62] presents compelling evidence that the use of in-service AE monitoring has resulted in a drastic reduction of catastrophic failures of fiber reinforced plastic tanks used in the chemical processing industry. Cole [63] describes the use of AE to assess

Many different types of mechanisms can generate acoustic emission. They include, but are not limited to, fracture and crack growth for fiber reinforced plastics [61]. These mechanisms can be characterized by the rapid relaxation of regions of material [61].

All real materials are inhomogeneous on a microscopic scale. For a metal bar that has locally anisotropic crystalline regions, as a tensile force is applied, the stress will reach a level where some of the randomly oriented crystals (and not others) will fracture. This will produce a sudden change in the local stress field and generate an acoustic emission which will propagate away from the fractured crystallite into the bar. Thus, the characteristics of an acoustic emission (amplitude, directionality, time of occurrence) depend on the local environment that produced it [61]. The local environment in this case is made up of the size and orientation of the fractured crystal and the size and orientation of neighboring crystals.

The case of fiber reinforced plastic composites is very similar. On a local level the material is highly anisotropic, and the weak areas (like the favorably oriented crystals in steel) are distributed throughout the material. For fiber reinforced plastics, these weak areas can be fibers (that are perhaps notched or simply on the low side of the average fiber strength) and resin rich areas (which may be susceptible to matrix cracking)

- What are the safety aspects involved in its application ?

- Can inspection keep pace with production ?

Based on these criteria and the literature reviewed [5,22,23,59,60], the nondestructive test methods chosen as favorable for use in this application are acoustic emission, visual inspection, ultrasonics, and proof testing. The following paragraphs describe: (1) basic principles of operation, (2) examples of proven performance, and (3) advantages of, acoustic emission (AE). The remaining NDT methods chosen (visual inspection, ultrasonics, and proof testing) will only be briefly detailed here in order to reduce the scope of this topic. These are already established, service-proven NDT methods for GRP ships. Acoustic emission has been emphasized due to its promise for widespread future shipboard use, even though it is unproven in applications of this magnitude.

Acoustic Emission

Acoustic emission (AE) can be defined as acoustic waves generated by a material. The difference between AE and the field known as ultrasonics is that in AE, there is no direct control over the mechanism that produces the acoustic wave. In ultrasonics, the acoustic wave is externally generated and introduced into the material. In AE, the material is subjected to conditions which cause the emission of the acoustic waves.

7. The selection of the NDT method for a specific application is vital to the eventual success or failure of the program. If the platform is over inspected, it could quickly become cost prohibitive. If under inspected, platform failure could result if critical defects are allowed to pass without correction. The NDT selected must fall between these two extremes. This selection must be based on a technical evaluation of the effect of defects as well as a thorough knowledge of the capabilities and limitations of the various NDT techniques. The test methods chosen must be currently available and field proven [22].

Several documented approaches have been used in other studies to provide a criteria for selecting the best NDT method. One approach [22] presented the following checklist to determine the suitability of various methods:

- Is it reliable ? What is the probability of an incorrect acceptance decision ?
- What is its sensitivity ? Will the method satisfy quality requirements ?
- What equipment is needed, and what is its cost ?
- What degree of operator skill is required to run tests and interpret data ?
- Is it applicable to primary structures ?
- Is the equipment commercially available or must it be developed ? Is extensive development necessary to adapt it to the production line ?
- Is it useful for other applications ?

length of the hull, whereas the cutouts are at specific locations.

(3) During the design phase, design and build test sections of various scaled dimensions. Once built, these sections can be exposed to various critical loadings including underwater shock and longitudinal bending. This type of testing is extremely expensive and time consuming, but necessary [14]. To possibly accelerate the gathering and eventual assessment of the data, it would be useful to request actual test data from the U.K., Italy, Sweden and other countries presently involved in GRP ship construction programs. A standard data collection form could be easily formatted and sent to the participating countries. Sharing this data would be an initial, important step toward some worthwhile consolidation of effort in this area.

Question 7.3: What nondestructive test methods should be used ?

This section will do the following: (1) describe the importance of selecting the proper nondestructive test, (2) present a criterion for that selection, and (3) select the test methods to be implemented.

Available nondestructive test (NDT) methods were presented in Section 3.3 and briefly described in Table

performance in actual loading conditions. The methods available to accomplish this purpose are not standard and vary depending on the application.

The methods that have been chosen are:

(1) Hull cutouts can be tested. A ship has designed into it many openings for access, piping and cabling runs, sea water suctions and discharges, etc. Testing the cutout material can verify: (a) resin to glass ratios, (b) proper materials and layup scheme used, (c) adhesion properties of the various interfaces, (d) water absorption properties, (e) void content or porosity, and (f) other physical properties. Note, based on the thickness of the hull, these cutouts may not be large enough to meet the dimensional requirements for ASTM test specimens. For example, the MWSX hull laminate would require a specimen length of 57.6 inches for the ASTM flexural strength test. This is based on a hull laminate thickness of 3.6 inches.

(2) During the actual layup of the hull, produce and test additional laminate test tabs. These tabs provide test samples that reflect the as built condition of the hull. Figure 35 depicts a candidate location for the test tabs. The Italians perform this test as they manufacture the Lerici Class minesweeper made of mono-skin GRP [58]. The difference between tabs and cutouts is that tabs are distributed along the entire

quality. A possible inconsistency arises when these defects are not placed in the proper perspective by comparing their relative importance to other defects. An advanced performance naval vehicle will demand more from standards than guidance based on workmanship experience.

In summary, the technical evaluation performed in Sections 4.1.1 through 4.1.5 showed that an equivalency between defects exists. This equivalency can aid in placing the defects (and the effort to control them) in perspective. For the specific ship evaluated, this equivalency served as justification to add the currently overlooked hole (with cracks) defect to the standards.

Question 7.2: What destructive tests should be used ?

The various destructive tests available have been detailed in Section 3.3. This Section will describe the purpose of destructive testing, and then present the methods chosen to accomplish this purpose.

The type and degree of destructive testing required is a difficult judgement. The purpose of destructive testing is to accomplish the following: (1) confirm nondestructive test results, (2) gain additional data on the statistics of defect distribution in order to better address the required inspection level and its periodicity, (3) measure material qualities which can not be obtained any other way, and (4) confirm material

has been produced, detected and evaluated as not allowable, it is necessary to provide procedures to correct that defect. Research has been performed in this area [5,13,14,33]. Various navies including the U.K., Sweden, Italy and the U.S. have developed both defect correction and post construction damage repair procedures. These procedures have been service proven based on their respective standards and specifications.

Current U.S.Navy standards prescribe the following repair procedures for the correction of internal defects (delaminations, voids, ply gaps, etc.) [23,33]:

1. Remove the part of the laminate that encloses the defect.

2. Grind the edges of the cut out to at least a 12 to 1 scarf.

3. Layup reinforcement to achieve original laminate thickness.

4. If the cutout is less than 24 square inches in area, the use of just chopped strand mat with polyester resin is allowed. For cutouts greater than 24 square inches, a combination of WR and CSM with polyester resin is required.

A 24 square inch cutout is equivalent to a 5.5 inch diameter hole if load transfer to the patch is improper. As described in Paragraph 4.1.5.3 a hole itself is a defect. If, while cutting out the enclosing laminate, a crack is introduced, a more severely degraded condition may possibly exist. In effect, the effort to correct a defect may introduce a more severe defect. Additional research into the degradation caused by correction

procedures is required to support quality control of advanced performance, low factor of safety ships.

Question 10: How can defects be evaluated ?

The answer to this question is to compare the defect the with the standards. The standards that address the allowable limits of key defects were discussed while answering Question 7.1. The adequacy of these standards was assessed based on the estimated effects of those key defects. This Section demonstrates that another consideration, defect location, is an equally important part of an effective standard. To accomplish this, example evaluations of several typical defects are made.

First, treatment by current standards of defect location is described. Then example evaluations are presented.

The following guidance was extracted from the <u>Inspection Manual For Fibrous Glass Reinforced Plastic Laminates</u> [23].

(a) No repairs will be allowed in highly stressed areas such as replenishment at sea hi-line connections or flange connections.

(b) If the size and location of an opening impairs the strength of an important structural member, it shall be reinforced. Important structural members are defined as longitudinal strength components and main

transverse bulkheads.

(c) Any portion of the ship (except highly stressed areas) found to contain defects that are not allowable shall be removed and replaced.

It is clear that the current standards only loosely tie in the location of the defect. If the defect is in an important or highly stressed area, some guidance is given. This is appropriate, but a more definite list of exactly what areas are important or highly stressed, and provisions for defects in areas of lower importance should be provided.

Not allowing repairs in highly stressed areas is probably a good idea since the amount of degradation caused by the repair is not well known.

Example #1

A single 0.75 inch void is detected visually in a non-structural bulkhead. The current standards call for this defect to be evaluated as unacceptable. Repair is mandatory. The proposed standard recognizes:

1. that a single 0.75 inch void has been estimated to reduce the failure stress by less than 10% (see Figure 22) and,
2. that the defect is located in a non-critical area.

Therefore, the proposed evaluation would be that the defect is allowable.

Example #2

A 5% void content is measured in a panel of the superstructure. The current standard evaluates this defect as unacceptable, and repair is mandatory. The proposed standard would recognize that a 5% void content reduces the failure stress by about 30% (See Figure 16). Since the superstructure is a non-critical area, the proposed evaluation would be that the defect is a strong candidate for a waiver. The 30% reduction in failure stress, though not small, is a magnitude that a low factor of safety should be capable of absorbing.

Example #3

A 6 inch diameter penetration is cut in the shell of the ship below the waterline for a flushing discharge connection. While cutting the hole, 2 small 1/2 inch notches were made accidentally. The current standard has no provision for inspecting or evaluating this defect. In fact, it is likely that this size penetration would not be considered to impair the longitudinal strength of the structure, and would therefore not even be reinforced. The proposed standard recognizes that this defect is estimated to reduce the failure stress by approximately 80% (see Table 10) in a critical area. Therefore, the proposed evaluation is that this defect is not acceptable and needs to be repaired.

These example evaluations demonstrate that the

current evaluation guidance is not adequate for an advanced naval platform because: (1) holes (with cracks) are not provided for, and (2) location has not been adequately considered.

Question 11: How can the QA be proportioned between the various stages of construction ?

This question has been partially answered in Question 8, but the pre-construction and in-process phases were only briefly discussed. The following guidance is provided to aid in proportioning the overall quality effort.

(1) Emphasis must be placed on material screening in the pre-construction phase. Constructing GRP ships requires raw materials to be combined on site. Ensuring that these raw materials meet the specifications and are handled and stored properly is a vital first step in assuring ship quality.

(2) Due to the labor intensive nature and the on site material manufacturing qualities of GRP, it is desirable to place emphasis on in-process inspection.

(3) Since the production process is responsible for the majority of defects produced, the in-process inspection of hull layup can provide immediate and simpler correction of defects. In-process visual inspection, though not sophisticated, can be effective and should be stressed. The use of highly trained and responsible

inspection technicians during the hull production and outfit stage can reduce the number of Type A and B defects while indirectly reducing production time by lowering rework and defect correction time.

(4) Since the use of GRP in a low factor of safety structural ship design is unproven, post-construction inspection of the hull is equally important as the other phases in assuring hull system reliability.

(5) The overall quality control effort is very broad and demands that complete records be kept for:

raw material - receipt, handlirg, and storage

in process - inspection and repair results

post construction - inspection and repair results.

A complete review and analysis of these data by qualified personnel is necessary to properly administer the level of quality assurance required by high performance naval ships of GRP construction.

The questions proposed (in Section 3.3) to determine the platform-dependent-technical attributes of a QAP (for an advanced performance naval vehicle) have been answered. Chapter 5 summarizes the major conclusions and provides recommendations to advance the development of quality assurance for GRP ship hulls.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.0 OVERVIEW

The scope of this thesis was purposely large in order to help solve a more practical, real world problem. The philosophy applied was to use a problem solving approach. The broad scope precluded a higher order analysis. This problem solving approach allows more complete consideration of the major practical problem of quality control of GRP ship hulls in naval applications while still making meaningful contributions toward the detailed solution.

The purpose of this chapter is to highlight the major thesis conclusions and recommendations.

5.1 CONCLUSIONS

The high factors of safety that dominate GRP structural designs indicate a lack of confidence in the material and fabrication methods. The limitations of currently available quality assurance techniques are largely responsible for this lack of confidence. For advanced composites used in the aerospace industry, the demand for lower factors of safety drive the development of improved QA techniques, which in turn allow lower factors of safety to be used in the design. This relationship between factor of safety and QA techniques is currently stagnant for GRP.

Even in the absence of future requirements for low design factors of safety, improved hull structure quality is important because it leads to improved hull system reliability. The improved reliability reduces the technical risk and could further promote the use of GRP in place of conventional shipbuilding materials. The U.S.Navy is presently building its first GRP ship. Since the use of GRP in large U.S.Naval ships it not yet demonstrated, hull system reliability will play an important role in shaping future demand for GRP in naval shipbuilding.

The key to hull system reliability is engineering the QAP to the specific application. Current QA guidance in the U.S. and in foreign countries appears to be based largely on production experience with small boats and pleasure craft. Additionally, this guidance is very general, and applies to almost any application of GRP construction. Although specifications unique to the application are required, the framework for that development is not adequate in the case of a low factor of safety structural design.

To improve this framework, the following significant management attributes of a low factor of safety QA plan were identified:

1. The quality assurance program (QAP) must be engineered to the ship construction program.
2. The QAP must exhibit effective organization to control the labor intensive nature of GRP ship construction.

3. The QAP must provide for training and certification of production personnel.
4. The QAP must provide for timely testing during the production process to monitor critical steps.
5. The QAP must provide continuous production process monitoring while maintaining quality records.
6. Keep the QAP simple, easy to implement while maintaining the correct level of QA based on the products design requirements.
7. GRP hull laminates are produced on site which requires an additional emphasis on material screening and in-process monitoring.
8. The quality effort must cover the three phases of ship construction (Pre, During, and Post). The proportioning of effort must be consistent with the design and production philosophy.
9. GRP is not a metal. The specifications and standards established for GRP must be tailored to the material used and the application.
10. There is a continuing tradeoff between cost, schedule, and quality. As a minimum, the product must adhere to the specifications and meet the design and performance requirements.

To help engineer the QA plan to any specific ship, the following series of questions were proposed:

1. What are the mission requirements ?
2. What are the platform requirements ?
3. What are the driving material design parameters ?
4. Where are the critical stresses and loads applied to the hull ?
5. What are the important defects ?
6. How can defects be prevented ?
7. How can defects be detected ?
8. How can the detection methods be integrated ?
9. How can defects be corrected ?
10. How can defects be evaluated ?
11. How is the overall quality control effort proportioned between the three phases of ship construction (Pre, During, and Post) ?

These questions were answered for a recently designed, low factor of safety GRP hull minewarfare ship (the MWSX). The effect, detection and evaluation of defects were emphasized.

An evaluation of existing models (almost all of which were developed for graphite reinforced composites) showed that: (1) cracks at the edges of hull penetrations could be critical defects that had not previously been considered important, (2) voids at reasonable contents are not significant, and (3) delaminations can be critical defects.

Following the selection of destructive and nondestructive detection methods, the following integrated

detection plan was proposed:

Pre-construction

A. Use of material screening was not addressed, but would continue to be a crucial part of the overall quality control method.

During-construction:

A. Use built in test tabs of extra hull laminate material for destructive testing.

B. Use a low resolution, high speed sonic technique equivalent to automated coin tapping.

C. Visual

Pre-service: (prototype hull only)

A. Use a proof test on the prototype hull with acoustic emission monitoring and high resolution ultrasonic transmission and visual follow up.

Post-construction: (for all ship hulls)

A. Use of acoustic emission as a continuous, in-service, global monitoring technique.

B. Use of ultrasonic transmission as a local monitoring technique to follow up on indications of damage from the AE monitoring system, and to thoroughly examine critical locations of the hull.

C. Visual

The adequacy of current standards was examined by using example evaluations of typical defects. It was demonstrated that the procedural guidance provided for defect control, evaluation and correction was not proportional to the importance of the defect. For example, there is currently no guidance for the hole with cracks defect. Additionally, current repair procedures call for the defective laminate to be cut out and replaced. This repair may introduce a more serious defect than it was meant to correct. These shortcomings of current standards must be adequately addressed before a lower factor of safety design can be realized.

The proposed methodology does provide a solid framework to engineer a quality plan to a ship. The results obtained from applying the methodology to the MWSX were revealing, even though a lack of applicable GRP research data limited our effort. Based on the outputs of several computer aided literature searches, there is little research being performed on the effect of defects in GRP structures. The majority of references used in this study were directed toward graphite reinforced composites.

5.2 RECOMMENDATIONS

In concluding this thesis, the following recommendations are summarized to provide direction for

continued research and improvement in the development of quality assurance for GRP ship hulls. For the convenience of the reader, the recommendations are listed in bullet format for clarity and emphasis.

- Future GRP ship construction programs should include requirements to perform a platform dependent approach similar to that proposed here in developing the QAP.

- The hole with cracks defect should be further investigated. Guidance concerning the inspection and correction of this defect should be developed and incorporated into the standards.

- A study should be conducted to examine if the use of acoustic emission for continuous in-service monitoring of GRP ship hulls is feasible.

- Bending proof tests on small GRP ships should be performed with AE instrumentation to establish baseline AE signatures. Additionally, much more is needed to be learned about the failure mechanisms of GRP in ship hull geometries.

- A bending proof test with AE instrumentation should be performed on a full scale prototype hull to certify the structural design, and confirm smaller scale test

results.

- The delamination models used in this study should be analytically adapted to the sandwich structure case. Figure 18 illustrates a suggested approach.

- Tests should be conducted to validate the following models used in this thesis:

    1. Shear propagation of delaminations in GRP beams: (a) use the same geometry as the graphite/epoxy beams of the original development, and (b) use the larger geometries associated with applying the model to a ship hull.
    2. Instability failure of GRP sandwich beams due to a delamination in the skin-core interface.
    3. The effect of a gap between ply edges of a GRP laminate.
    4. The effect of holes with cracks in GRP laminates.

- Procedures to correct defects must be thoroughly studied. The risk of introducing a more severe defect than the one being corrected must be eliminated.

- A survey of GRP production yards should be made to determine, if while cutting hull penetrations, cracks or notches are induced.

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MICROCOPY RESOLUTION TEST CHART
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- A statistically based approach to current test techniques should be developed. If the introduction of defects into the laminate is indeed random, a statistically based test would predict a probability of reliability.

- Pre-construction test programs and full scale testing of midships sections are an important part of the building of a new class of ships. Many countries involved with construction of GRP naval ships conduct these tests independently. As a result, unnecessary repetition of these expensive test programs occur. The data that are made available are often only through a public relations medium. By a internationally coordinated review of what has been accomplished to date, valuable test information could be obtained, and additional project funds would become available for improvements in QA.

- A prototype test platform is needed for conducting shipboard testing to gain in-service data. A low mix GRP hull coastal minesweeper/hunter would be an ideal candidate.

- The first class of ships with a reduced factor of safety should have a continuous in-service monitoring system installed to provide real time information about damage development.

- In the opinion of the Authors, prefabrication production techniques offer enormous potential for improvements in GRP ship construction quality. A study to evaluate the potential application of these techniques should be performed.

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TABLE 1

ADVANTAGES AND DISADVANTAGES OF GLASS REINFORCED PLASTICS [1]

ADVANTAGES	DISADVANTAGES
- HIGH STRENGTH TO WEIGHT RATIO	- LOW ELASTIC MODULUS
- ABILITY TO FABRICATE LARGE, COMPLEX SHAPES IN ONE PIECE	- INITIAL MOLD COSTS
- NON-MAGNETIC	- COMBUSTIBLE
- EASE OF MAINTENANCE & REPAIR	- HIGH MATERIAL AQUISITION COSTS
- RADAR & ACOUSTICALLY TRANSPARENT	- BRITTLE, LOW STRAIN TO FAILURE
- LOW THERMAL CONDUCTIVITY	- MATERIAL HIGHLY ANISOTROPIC
- CORROSION RESISTANT	- LOW INTER-LAMINAR SHEAR STRENGTH
- HIGHLY GLOSSED SURFACE FINISH IS PRODUCT OF LAYUP	- EXTREMELY DIFFICULT TO CHECK THE QUALITY OF LARGE STRUCTURES
- LARGE VARIATION OF MECHANICAL PROPERTIES AVAILABLE OVER WIDE SELECTION OF FIBER-MATRIX MATERIAL SYSTEMS	- LONG TERM SEA WATER IMMERSION DEGRADES MATERIAL PERFORMANCE
- MATERIAL LIFE CYCLE COSTS ARE COMPETITIVE WITH OTHER MATERIALS	- STRUCTURES DEFLECTION LIMITED
- FABRICATION COSTS ARE DECREASING AS IMPROVED PRODUCTION METHODS ARE DEVELOPED	- IF NOT PAINTED, MATERIAL APPEARANCE DEGRADES DUE TO ENVIRONMENTAL ATTACK
	- LITTLE SERVICE EXPERIENCE

TABLE 2

SUMMARY OF EXISTING GRP MINE WARFARE SHIPS [3]

Country	Class	Length (ft)	Displ. (Ltons)	Entered Service	Number Planned	Const Notes
Australia	Catamaran	101	160	Mid-80's	6	1
Belguim	Tripartite	154	544	80-87	10	2
France	Tripartite	154	544	80-87	15	2
Italy	Lerici	163	500	1983	10	3
Malaysia	Mahamiru	163	500	1984	4	3
Netherlands	Tripartite	154	544	80-87	15	2
Sweden	M80	155	340	1984	6	1
U.K.	Wilton	152	450	1973	1	2
U.K.	Hunt	197	725	1980	12	2
USSR	Zhenya	140	300	1970	3	-
USSR	Andryusha	147	360	1975	2	5
USSR	Sonya	160	460	1973	42	4

Construction Notes :

1. GRP foam core sandwich
2. GRP single skin-stiffened
3. GRP single skin-monocoque
4. Wood with GRP sheathing
5. GRP structure but not confirmed in literature

<u>TABLE 3</u>

<u>COMPARISON OF VARIOUS SHIPBUILDING MATERIALS [2,3,]</u>

MATERIAL PROPERTY	GRP	STEEL	ALUM	S.S.	TITANIUM	WOOD
YOUNG'S MODULUS (PSI x 10[illegible])	2	29	10.6	28	16.7	1.9
ULTIMATE STRENGTH (PSI x 10[illegible])	20	33	20	36	135	6.4
DENSITY (LB/IN³)	0.062	0.282	0.097	0.286	0.17	0.02
SPECIFIC MODULUS (PSI x 10[illegible]/LB/IN³)	3.2	10	11	9.8	10	9.5
SPECIFIC STRENGTH (PSI x 10[illegible]/LB/IN³)	3.2	1.2	2.1	1.3	7.9	3.2

TABLE 4

RELATIVE COMPARISONS OF GRP
WITH OTHER SHIPBUILDING MATERIALS [3]

MATERIAL	* DRIVING PROPERTY MAGNETIC SIGNATURE COMPARISON	LIGHT SHIP STRUCTURAL WEIGHT COMPARISON	MATERIAL ACQUISITION COST COMPARISON	ASPECTS OF PRODUCIBILITY COMPARISON
ALUMINUM	GREATER THAN GRP	23% HEAVIER THAN GRP	LESS THAN GRP	LESS RISK THAN GRP
STAINLESS STEEL	GREATER THAN GRP	47% HEAVIER THAN GRP	EQUAL	HIGHER RISK THAN GRP
TITANIUM	** EQUAL	LESS THAN GRP	13 TIMES GREATER	HIGHER RISK THAN GRP
WOOD	EQUAL	25% HEAVIER THAN GRP	*** EQUAL	HIGHER RISK THAN GRP

* All comparisons made with respect to GRP CSM-WR in PE matrix.

** Titanium is a non-magnetic material but not proven on ship magnetic range trials.

*** Wood cost does not include 50% wastage allowance.

TABLE 5 *

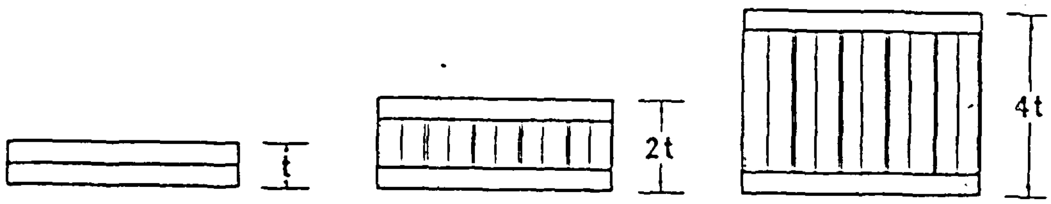
NORMALIZED COST COMPARISON BETWEEN STEEL AND GRP SANDWICH SHIP STRUCTURES [5]

Comparison	Material	
	Steel	GRP Sandwich
Material cost	100	105-115
Production Hours:		
General	100	115-130
hull deckhouse	100	75-95
Hull Equip	100	55-75
Prop. Mach.	100	80-95
Other Mach.	100	80-95
Electronic	100	85-95
Equip. Mount	100	85-95
Total	100	75-95

* Based on the construction of 5 or more identical ships in the 70-450 T range, 25-60 meters in length.

FIGURE 6

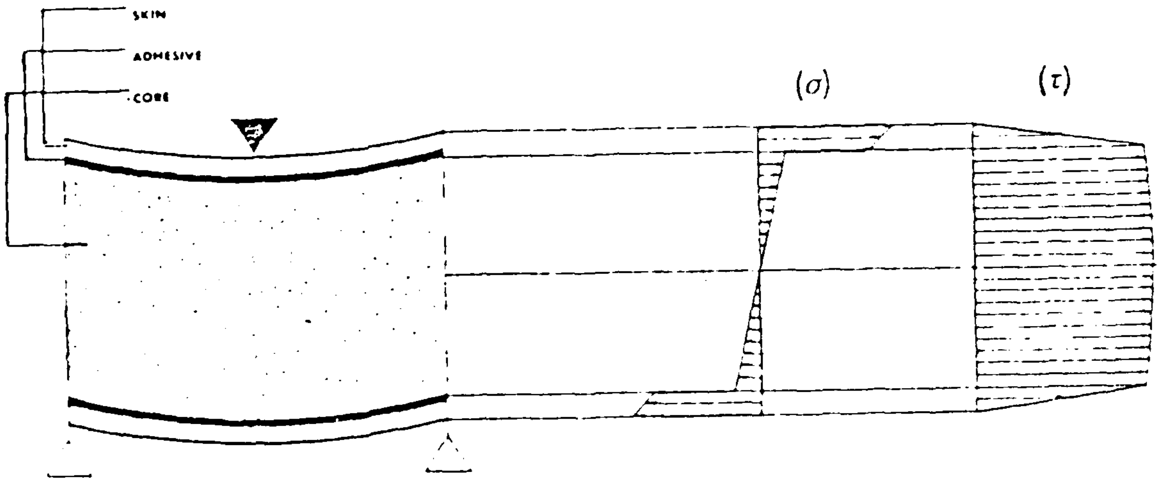
AN EXAMPLE OF INCREASING FLEXURAL RIGIDITY WITHOUT INCREASING WEIGHT [2]



Stiffness (D)	1583 lb-in^2/in. (1822 kg-cm^2/cm)	11,669 lb-in^2/in. (13,933 kg-cm^2/cm)	61,674 lb-in^2/in. (71,004 kg-cm^2/cm)
Relative values	(1.0)	(7.4)	(39.0)
Weight	1.79 lb/ft^2 (29 kg/m^3)	1.85 lb/ft^2 (30 kg/m^3)	1.90 lb/ft^2 (30 kg/m^3)
Relative values	(1.00)	(1.03)	(1.06)

FIGURE 5

STRESS DISTRIBUTION IN A SANDWICH BEAM SUBJECTED TO BENDING [14]



BENDING (σ) AND SHEAR (τ) STRESS DISTRIBUTION IN A SANDWICH BEAM SUBJECTED TO BENDING.

FIGURE 4

SANDWICH MATERIAL COMPONENTS [2]
(Equivalent I-Beam)

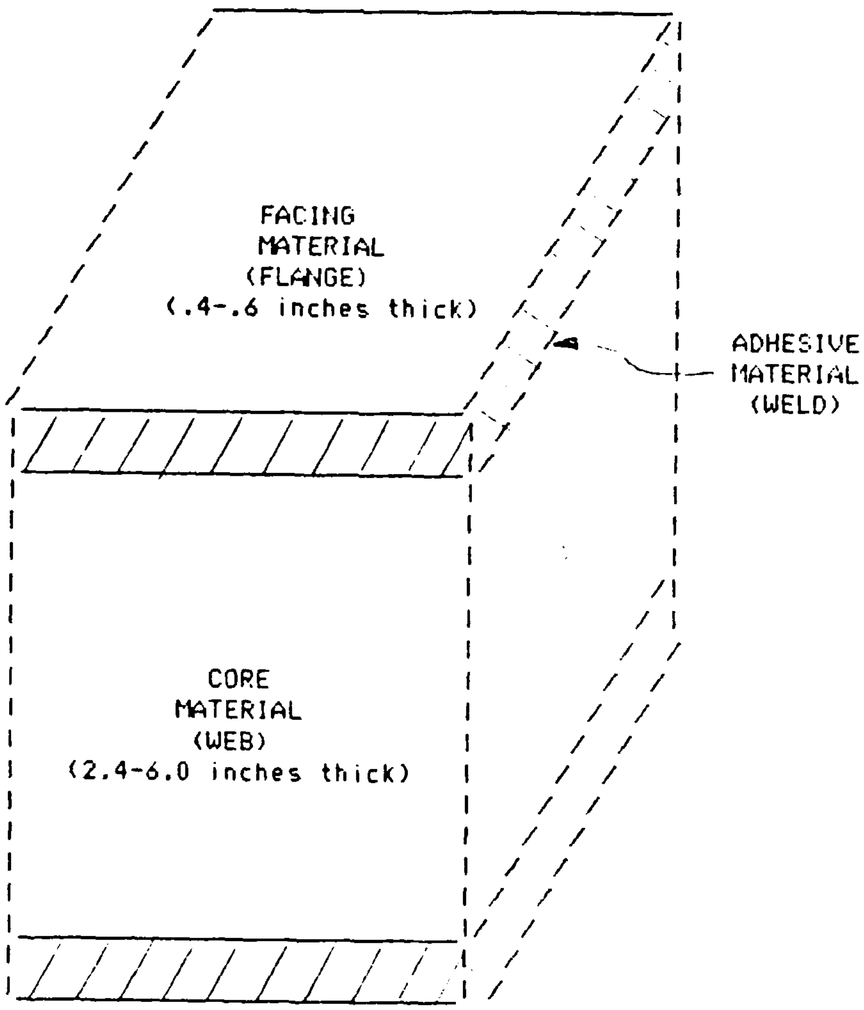


FIGURE 3

STRESS STRAIN CURVES FOR CANDIDATE MINESWEEPER HULL MATERIALS [6]

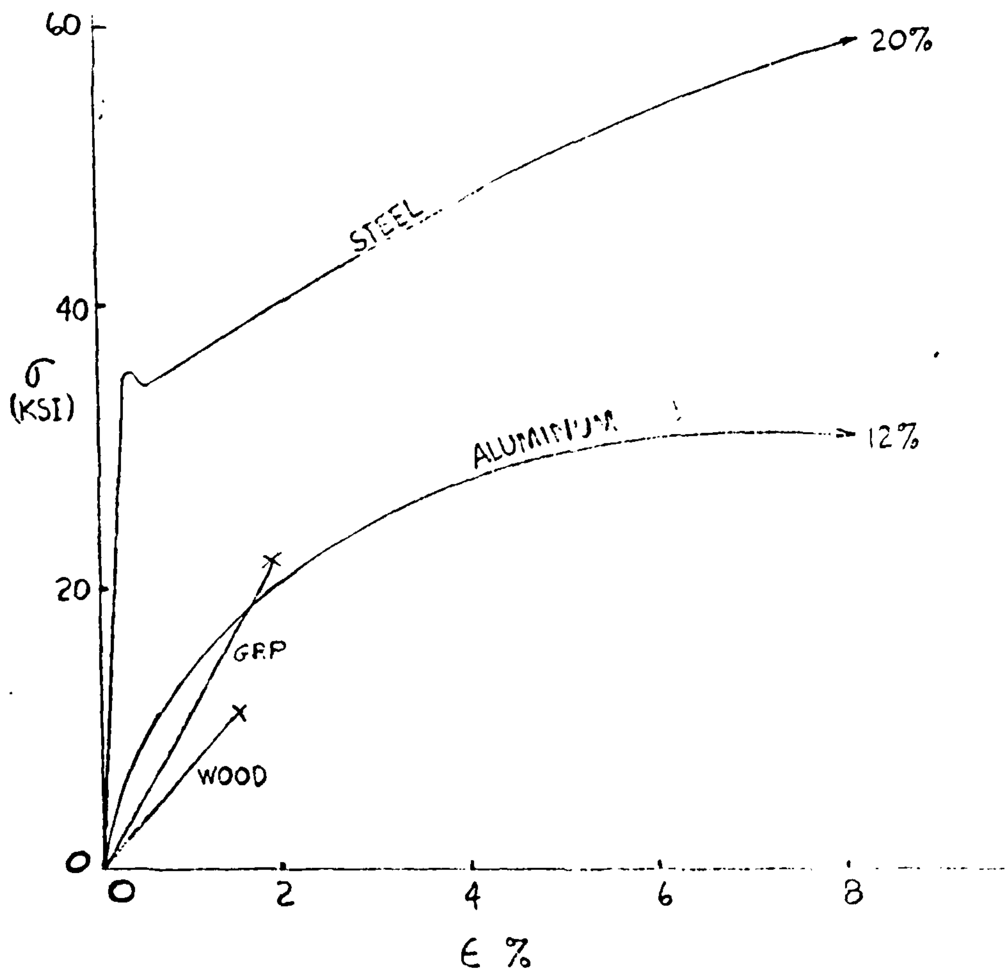


FIGURE 2

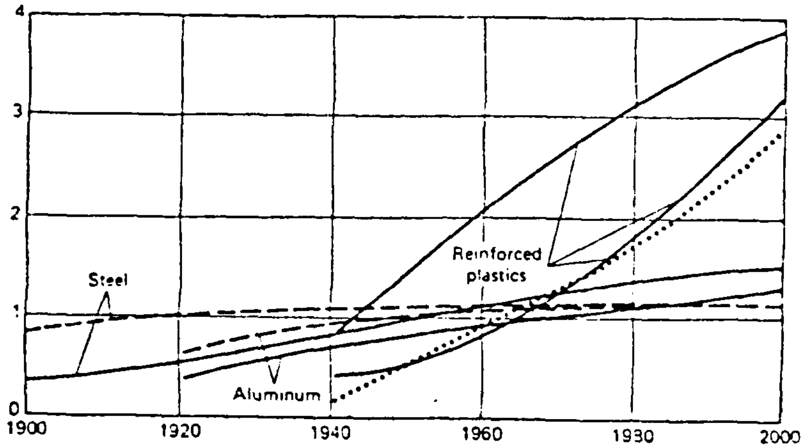
REASONS TO USE GLASS REINFORCED PLASTICS

Advantages of use outweigh the disadvantages

- comparable acquisition costs
- reduced operating and support cost
- improved hull material performance
    - reduced structural weight by 21% [3]
    - provides a 6dB reduction in radiated noise [1]
    - reduced hull maintenance [5]
    - non-magnetic
    - reduces electrical requirements due to hull insulation
    - reduces the complexity of repairs [5]
- improved producibility
- moderate to low technical risk
- advance GRP technology
- lighter ship-shallower draft-reduced pressure signature [17]

FIGURE 1

FORECAST GROWTH IN UNIDIRECTIONAL STRENGTH PROPERTIES OF REINFORCED PLASTICS AND CONVENTIONAL MATERIALS



Past and forecasted growth in the unidirectional structural properties of RP and conventional materials. Ratio of tensile (———) or compressive (· · · ·) strength (psi) to density (lb/cu in.) × 10^6. Ratio of tensile modulus of elasticity (psi) to density (lb/cu in.) × 10^8 (----).

TABLE 13

SUMMARY OF EXAMPLE EVALUATIONS

DEFECT	LOCATION	EVALUATION OLD / PROPOSED *
A SINGLE 0.75 in. VOID	NON-STRUCTURAL BULKHEAD	NOT ALLOWABLE / ALLOWABLE
5% VOID CONTENT	SUPERSTRUCTURE PANEL	NOT ALLOWABLE / ALLOWABLE
6 in. DIAMETER HOLE WITH TWO .5 in. CRACKS	SHELL BELOW WATERLINE	NO PROVISIONS FOR EVALUATION / NOT ALLOWABLE

* BASED ON ESTIMATES OF EFFECTS OF DEFECTS PARAGRAPH 4.1

TABLE 12

SUMMARY OF THE EFFECTS OF DEFECTS FOR GLOBAL AND LOCAL LOADING

	CRITICAL DEFECT	
	GLOBAL BENDING *	LOCAL BENDING **
	(a in inches)	
SHEAR PROPAGATION OF DELAMINATION MODE II	a = 59	a = 6
INSTABILITY FAILURE DUE TO DELAMINATION	a = 14	a = 14
NO HOLE JUST CRACK MODE I	a = 4.3	a = 4.3
12 in. DIAMETER HOLE WITH CRACK MODE I	a = .75	a = .75
24 in. DIAMETER HOLE WITH CRACK MODE I	a = .75	a = .75
48 in. DIAMETER HOLE WITH CRACK MODE I	a = .40	a = .40
VOID CONTENT	V_v = 21%	V_v = 21%

* @ MAXIMUM BENDING MOMENT

** @ σ = 2970 psi

TABLE 11

COMPARISON OF PROPERTIES FOR
DISCONTINUOUS, STAGGERED LAYUP TO CONTINUOUS LAYUP

	0^{o}	90^{o}
TENSILE STRENGTH	− 8.8%	+ 1.4%
TENSILE MODULUS	− 7.4%	+ 3.9%
SHORT BEAM SHEAR STRENGTH	0.0%	− 12.9%
COMPRESSIVE STRENGTH	− 12.8%	+ 7.2%
COMPRESSIVE MODULUS	− 1.2%	+ 2.9%

ALL STRENGTHS X 10^{3} psi

ALL MODULI X 10^{6} psi

TABLE 10

CRITICAL CRACK SIZE FOR HOLES
WITH CRACKS IN 8 ft. X 8 ft. PANEL OF GRP

HOLE DIAMETER (inches)	CRACK SIZE TO FAIL (inches)
0	4.3
12	.75
24	.40
48	.24

TABLE 9

STRESS CONCENTRATIONS FOR CIRCULAR HOLES IN AN 8 ft. X 8 ft. PANEL OF GRP

HOLE DIAMETER (inches)	ISOTROPIC STRESS CONCENTRATION	APPROXIMATE ORTHOTROPIC STRESS CONCENTRATION
.5	3.02	3.93
1	3.03	3.94
2	3.04	3.95
4	3.07	3.99
26	3.57	4.64
48	4.60	5.98
62	5.08	6.60
76	8.40	10.92
84	12.80	16.64

TABLE 8

CRITICAL DELAMINATION SIZE FOR FAILURE IN GLOBAL AND LOCAL LOADING

LOADING	SHEAR PROPAGATION OF DELAMINATION	INSTABILITY FAILURE DUE TO DELAMINATION
GLOBAL (Maximum Moment)	59 in.	14 in.
LOCAL (σ = 2970 psi)	6 in.	14 in.

TABLE 7

COMPARISON OF SEVERAL NDE METHODS [32]

Method	Chapter	Properties sensed or measured	Typical flaws detected	Representative application	Advantages	Limitations
X-ray radiography	4	Inhomogeneities in thickness, density, or composition.	Voids, porosity, inclusions, and cracks.	Castings, forgings, weldments, and assemblies.	Detects internal flaws; useful on a wide variety of materials; portable; permanent record.	Cost; relative insensitivity to thin laminar flaws such as fatigue cracks and delaminations; health hazard.
Neutron radiography.	4	Compositional inhomogeneities; selectively sensitive to particular atomic nuclei.	Presence, absence, or mislocation of internal components of suitable composition.	Inspection of propellant or explosive charge inside closed ammunition or pyrotechnic devices.	Good penetration of most structural metals, high sensitivity to favorable materials; permanent record.	Cost; relatively unportable; poor definition; health hazard
Liquid penetrants	2	Material separations open to a surface.	Cracks, gouges, porosity, laps, and seams.	Castings, forgings, weldments, and components subject to fatigue or stress-corrosion cracking.	Inexpensive; easy to apply; portable.	Flaw must be open to an accessible surface, messy; irrelevant indications often occur, operator dependent.
Eddy-current testing.	5	Anomalies in electric conductivity and, in cases, magnetic permeability.	Cracks, seams, and variations in alloy composition of heat treatment.	Wire, tubing, local regions of sheet metal, alloy sorting, and thickness gaging	Moderate cost; readily automated; portable; permanent record if needed.	Conductive materials only; shallow penetration, geometry sensitive, reference standards often necessary.
Microwave testing	7	Anomalies in complex dielectric coefficient; surface anomalies in conductive materials.	In dielectrics: disbonds voids, and large cracks; in metal surfaces surface cracks.	Glass fiber-resin structures; plastics; ceramics; moisture content; thickness measurement.	Noncontacting; readily automated; rapid inspection.	No penetration of metals; comparatively poor definition of flaws
Magnetic particles	8	Anomalies in magnetic field flux at surface of part.	Cracks, seams, laps, voids, porosity, and inclusions.	Castings, forgings, and extrusions.	Simple; inexpensive; senses shallow subsurface flaws as well as surface flaws.	Ferromagnetic materials only, messy; careful surface preparation required; irrelevant indications often occur; operator dependent.
Magnetic field testing	8	Anomalies in magnetic field flux at surface of part.	Cracks, seams, laps, voids, porosity, and inclusions.	Castings, forgings, and extrusions.	Good sensitivity to and discrimination of fatigue cracks; readily automated, moderate depth penetration; permanent record if needed.	Ferromagnetic materials only, proper magnetization of part sometimes difficult.
Ultrasonic testing	3	Anomalies in acoustic impedance.	Cracks, voids, porosity, and and delaminations.	Castings, forgings, extrusions; thickness gaging	Excellent penetration, readily automated; good sensitivity and resolution requires access to only one side; permanent record if needed.	Requires mechanical coupling to surface; manual inspection is slow; reference standards usually required; operator dependent.
Sonic testing	3	Anomalies in low-frequency acoustic impedance or natural modes of vibration.	Disbonds, delaminations, larger cracks or voids in simple parts.	Laminated structures; honeycomb, small parts with characteristic "ring".	Comparatively simple to implement; readily automated, portable.	Geometry sensitive, poor definition.
Ultrasonic holography	3	Same as ultrasonic testing	Same as ultrasonic testing	Inspection of small, geometrically regular parts.	Produces a viewable image of flaws	Cost; limited to small parts poor definition compared to radiography
Infrared testing	6	Surface temperature; anomalies in thermal conductivity and/or surface emissivity.	Voids or disbonds in nonmetallics; location of hot or cold spots in thermally active assemblies.	Laminated structures; honeycomb; electric and electronic circuits.	Produces a viewable thermal map.	Cost; difficult to control surface emissivity, poor definition.
Strain gages	10	Mechanical strains	Not used for flaw detection	Stress-strain analysis of most materials.	Low cost; reliable	Insensitive to preexisting strains, small area coverage, requires bonding to surface
Brittle coatings	10	Mechanical strains	Not commonly used for flaw detection.	Stress-strain analysis of most materials.	Low cost; produces large area map of strain field.	Insensitive to preexisting strains, messy limited accuracy
Optical holography	11	Mechanical strains	Disbonds; delaminations; plastic deformation.	Honeycomb, composite structures, tires, precision parts such as bearing elements.	Extremely sensitive; produces map of strain field; permanent record if needed.	Cost; complexity, requires considerable skill.
Leak detection	9	Flow of a fluid	Leaks in closed systems	Vacuum systems; gas and liquid storage vessels; piping.	Good sensitivity; wide range of instrumentation available	Requires internal and external access to system; contaminants may interfere; can be costly.

TABLE 6

FORECAST OF DEMAND FOR REINFORCED PLASTICS [7]

Millions of lb	1985 *	1984	1983	1982	1981	1980	1975
Transportation, land	570	540	458	359	445	416	265
Construction	443	430	400	312	309	297	175
Anticorrision	326	310	283	235	275	252	163
Marine	325	309	276	230	290	275	285
Electrical	205	187	170	140	178	162	82
Consumer Goods	149	143	128	84	110	103	64
Appliance	130	123	106	82	112	104	64
Aircraft	35	29	25	22	28	25	24
Other	86	80	72	64	74	70	53
TOTAL	2269	2153	1923	1528	1821	1694	1175

ANNUAL CHANGE %	1984-85 *	1983-84	1980-85	1975-85
Tansportation, land	5.6	17.9	6.5	8
Construction	3	7.5	9.1	9.7
Anticorrosion	5.2	7.6	5.3	7.2
Marine	5.5	12	3.4	1.3
Electrical	8.5	11.2	4.8	9.6
Consumer goods	4.2	11.7	7.7	8.8
Appliance	5.7	16	4.6	7.3
Aircraft	20.7	16	7	3.8
Other	7.5	11.1	4.2	5
TOTAL %	5.4	12	6	6.8

* forecast; remaining are actual.

FIGURE 7

COMPARISON OF FACTOR OF SAFETY AND STRUCTURAL WEIGHT FOR VARIOUS MATERIALS [3]

* Factor of safety comparison for structural weight

Material	Factor of Safety
steel	3.3
aluminum	5.6
wood (Fir)	6.0
GRP (Sandwich)	6.7

* Structural weight for equal factor of safety

Material	Structural Weight (LTons)
steel	590
aluminum	495
wood (FIR)	500
GRP (Sandwich)	401

FIGURE 8

FACTOR OF SAFETY VS STRUCTURAL WEIGHT FOR AN ADVANCED PERFORMANCE NAVAL SHIP [3]

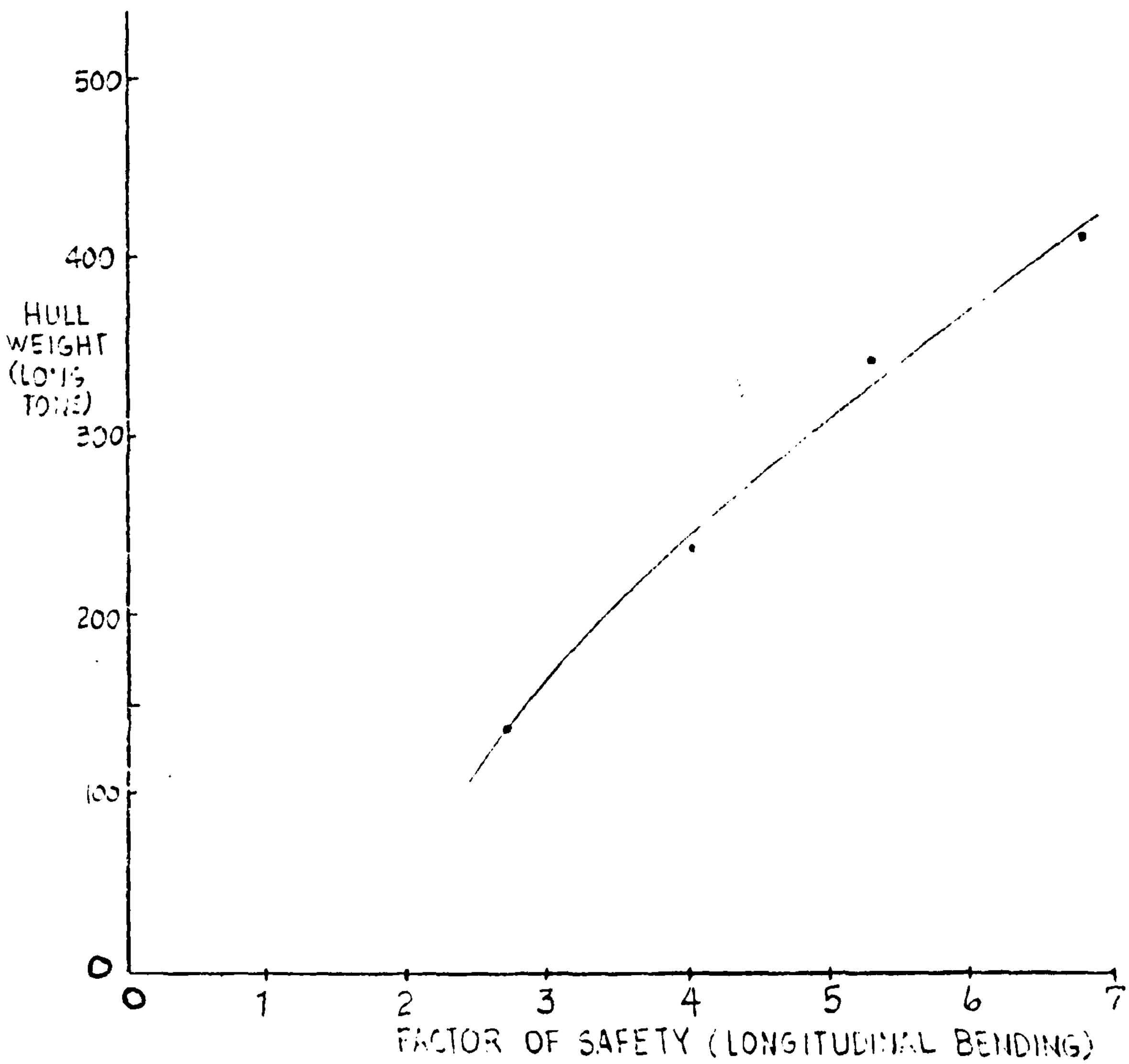


FIGURE 9

COMPONENTS OF A TYPICAL FACTOR OF SAFETY FOR A GRP SHIP DESIGN [5]

The allowable stress can be written as :

$$\sigma_{Design} = \frac{\sigma_{ult}}{S*G}$$

Where G= (G1)x(G2)x(G3)x(G4) = safety factor correction factor

σ_{ult} = The ultimate strength

S = Safety Factor = 2.5

G1(static) = 2.0 caused by creep

G1(dynamic) = 1.35 caused by alternating loads

G2 = 1.2 caused by aging of material

G3 = 1.2 caused by nonisotropic properties

G4 = 1.2 caused by defective handling in workshops

Static load total design factor = G(static)

Dynamic load total design factor = G(dynamic)

G(static) = (2.0)(1.2)(1.2)(1.2) = 3.46

G(dynamic) = (1.35)(1.2)(1.2)(1.2) = 2.33

Therefore: effective safety = (S)(G) = 8.65 for static case

= 5.83 for dynamic case

FIGURE 10

FLOW CHART OF METHODOLOGY FOR DEVELOPING
ATTRIBUTES OF QUALITY ASSURANCE PLAN FOR GRP

TECHNICAL ATTRIBUTES

ANSWER THE FOLLOWING QUESTIONS AND PROVIDE OPTIONS AND HINTS OF SELECTION WHERE APPLICABLE

1. WHAT ARE THE MISSION REQUIREMENTS ?
2. WHAT ARE THE PLATFORM REQUIREMENTS ?
3. WHAT ARE THE DRIVING MATERIAL DESIGN PARAMETERS ?
4. WHERE ARE THE STRESS CRITICAL AREAS OF THE SHIP ?
5. WHAT ARE THE IMPORTANT DEFECTS ?
6. HOW CAN DEFECTS BE PREVENTED ?
7. HOW CAN DEFECTS BE DETECTED ?
8. HOW CAN THE DETECTION METHODS BE INTEGRATED ?
9. HOW CAN DEFECTS BE CORRECTED ?
10. HOW CAN DEFECTS BE EVALUATED ?
11. HOW CAN THE QA EFFORT BE PROPORTIONED BETWEEN THE VARIOUS STAGES OF CONSTRUCTION ?

MANAGEMENT ATTRIBUTES

CHOOSE THE DESIRED ATTRIBUTES FROM ESTABLISHED AND SUCCESSFUL QUALITY PLANS (LABOR INTENSIVE PROGRAMS)

ADAPT THE ATTRIBUTES TO THE SHIP HULL CONCEPT DUE DIFFERENCES OF THE PRODUCTION METHODS

APPLY TO A SPECIFIC CASE

FIGURE 11

ADVANCED COMPOSITE QUALITY ASSURANCE PROGRAM [22]

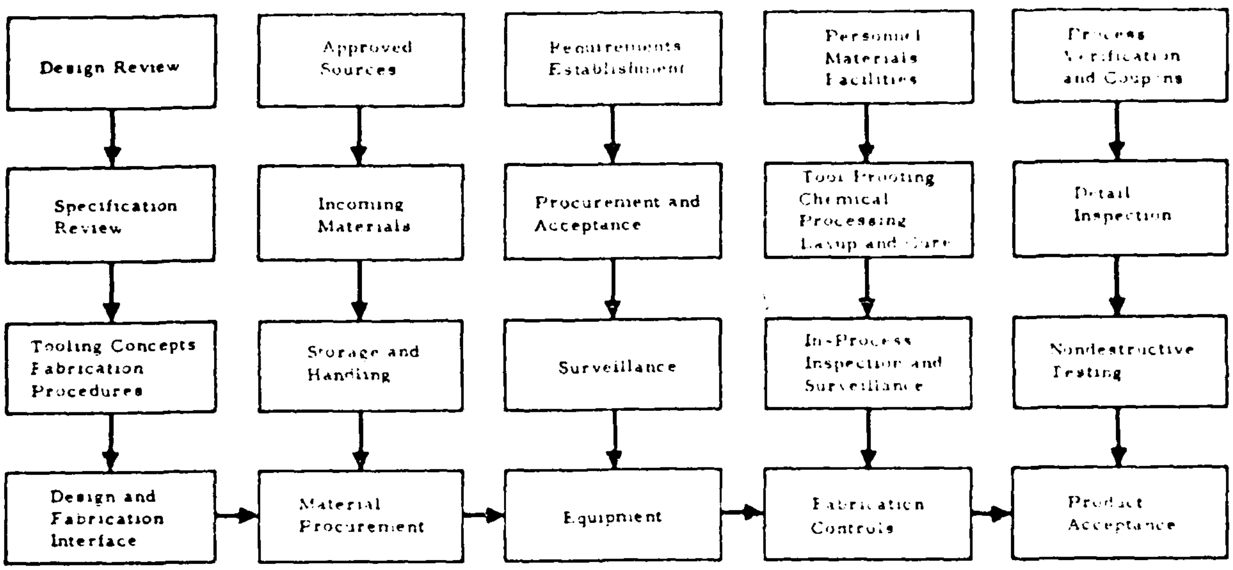
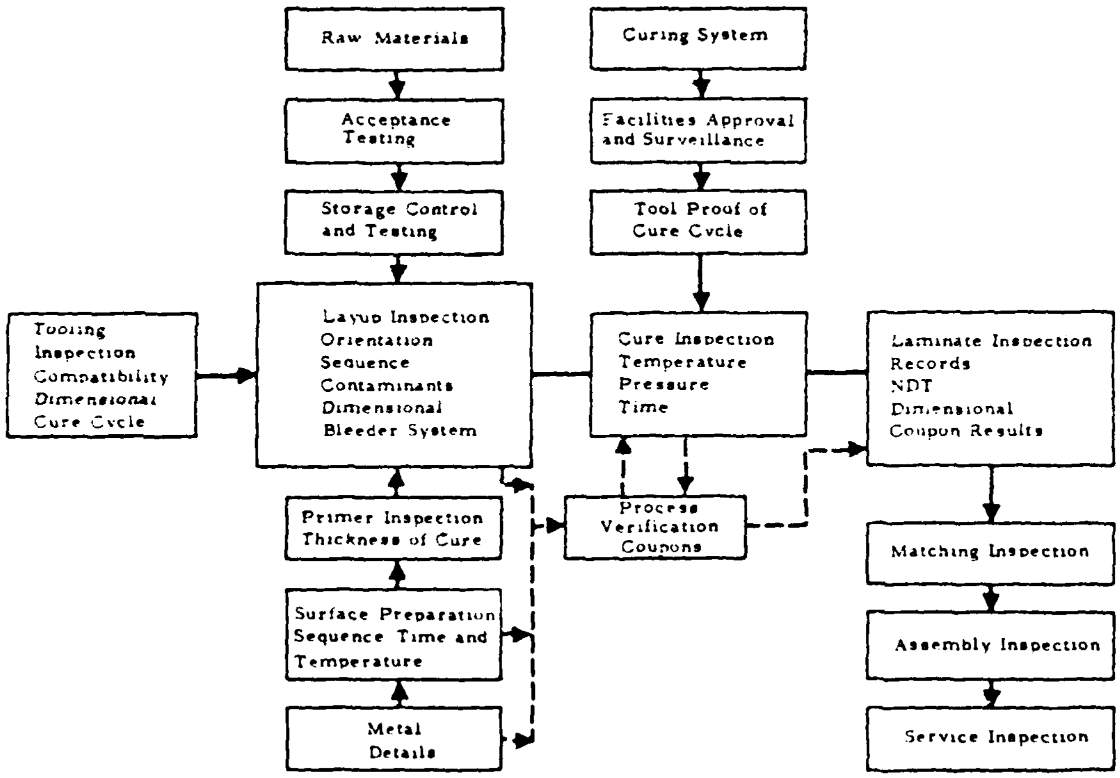


FIGURE 12

INSPECTION REQUIREMENTS FOR COMPOSITE MATERIALS [22]



INSPECTION REQUIREMENTS FOR COMPOSITE MATERIALS

FIGURE 13

TYPICAL METHODOLOGY FOR DEVELOPING ATTRIBUTES OF A QUALITY ASSURANCE PLAN FOR ADVANCED PERFORMANCE COMPOSITES [22]

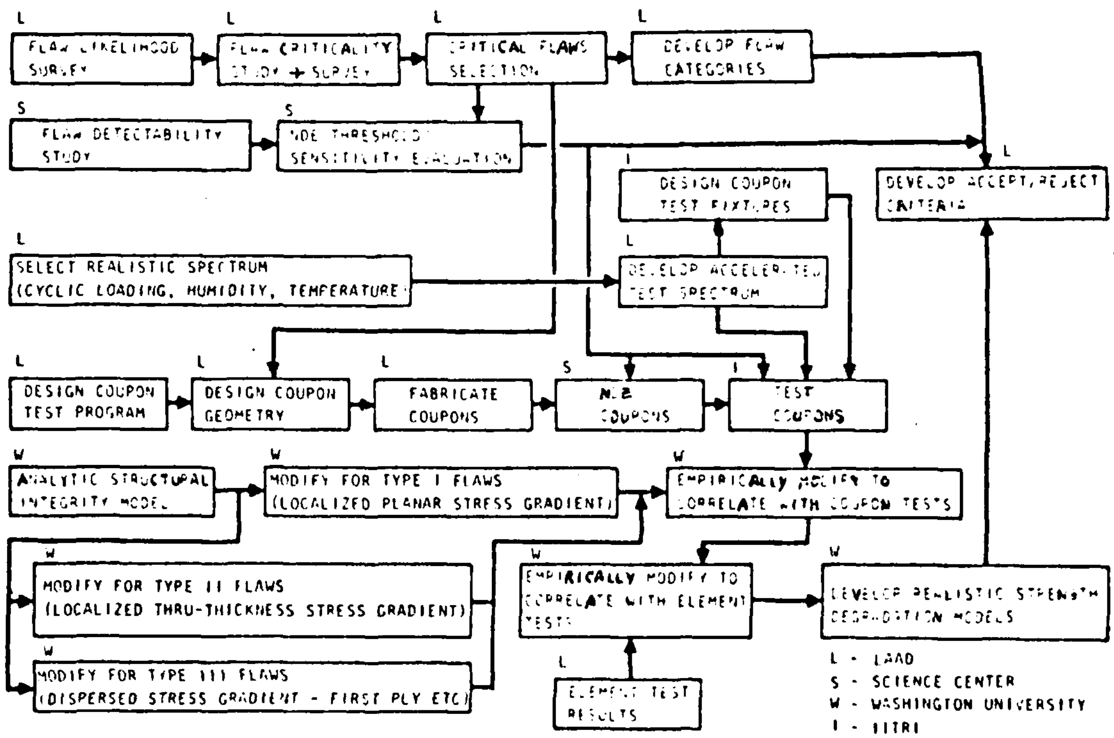


FIGURE 14

THE EFFECT OF VOID CONTENT
ON INTERLAMINAR SHEAR STRENGTH [37]

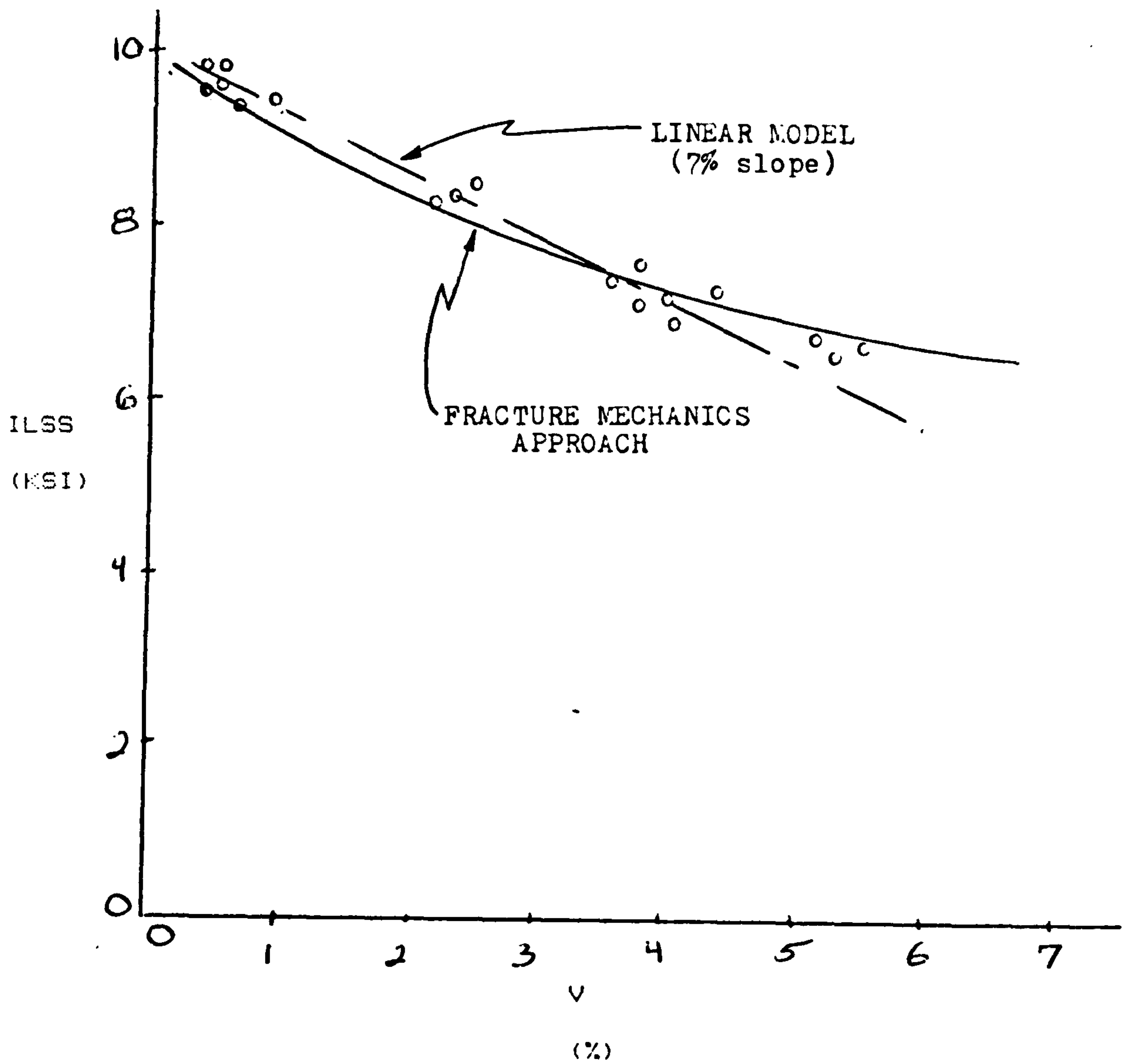


FIGURE 15

THE EFFECT OF VOID CONTENT ON COMPRESSIVE STRENGTH

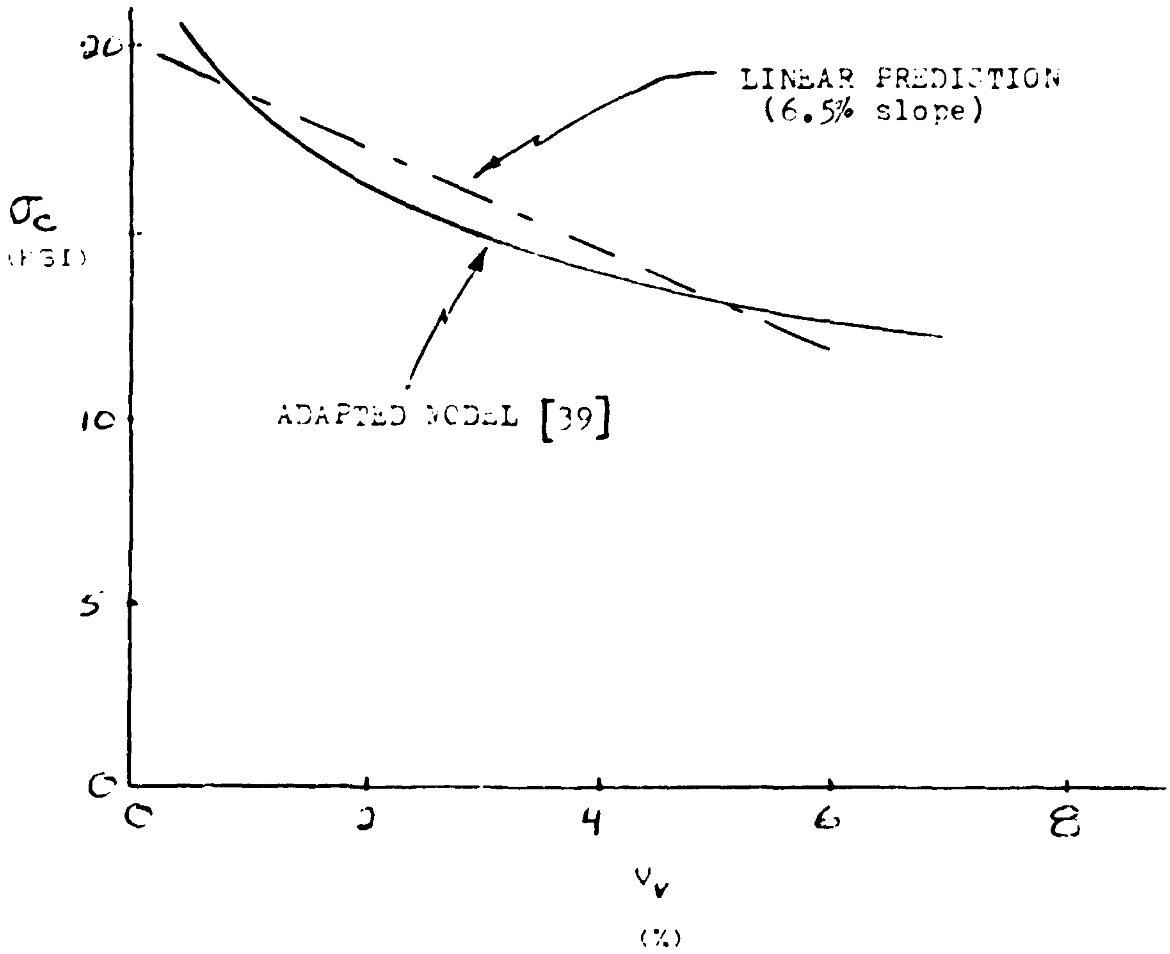


FIGURE 16

RESULTS OF VOID CONTENT MODEL

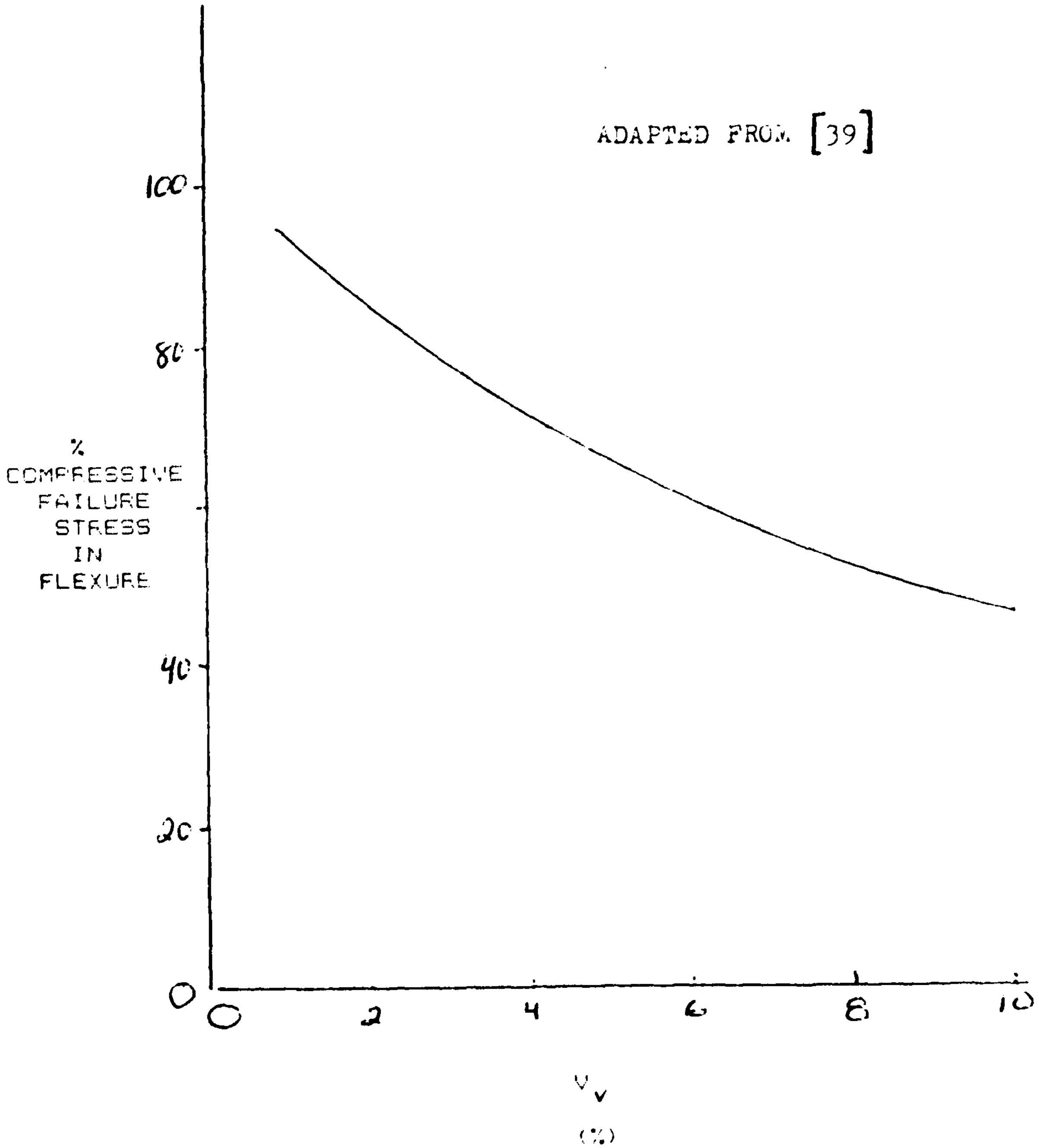
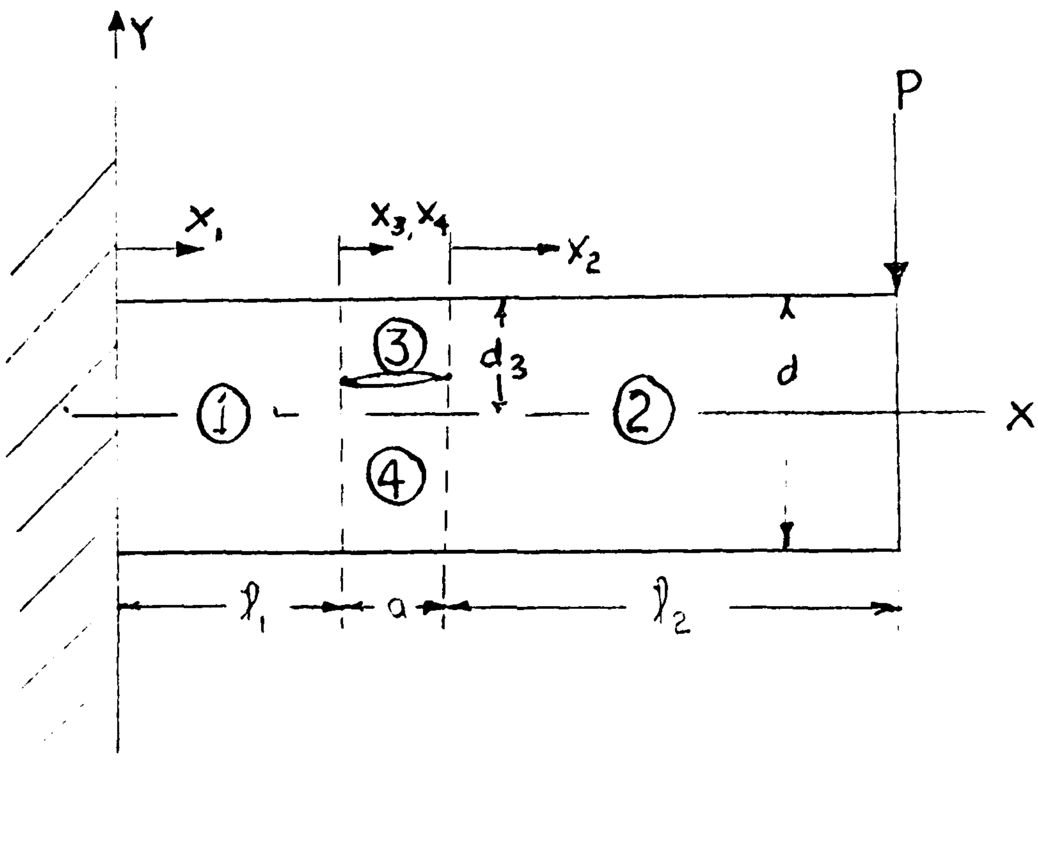


FIGURE 17

CONFIGURATION OF BEAM ELEMENTS FOR SHEAR PROPAGATION OF DELAMINATION MODEL [40]



4 BEAM ELEMENTS JOINED AT CRACK TIPS

FIGURE 18

PROPOSED BEAM ELEMENT CONFIGURATION TO ACCOUNT FOR SANDWICH COMPONENTS

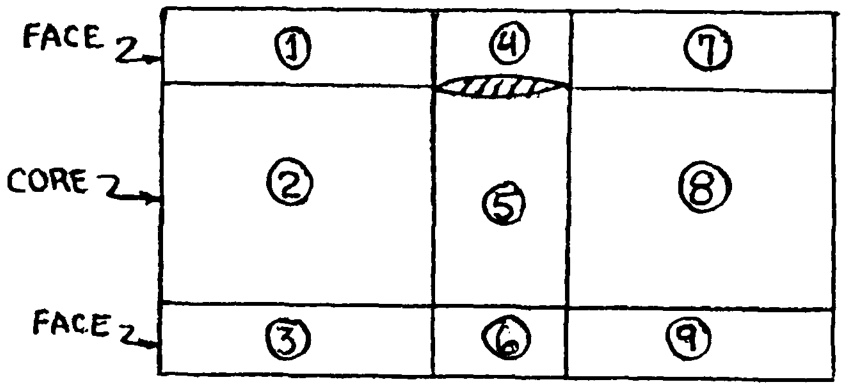


FIGURE 19

LOCATION OF ELEMENTS ON ACTUAL SHIP

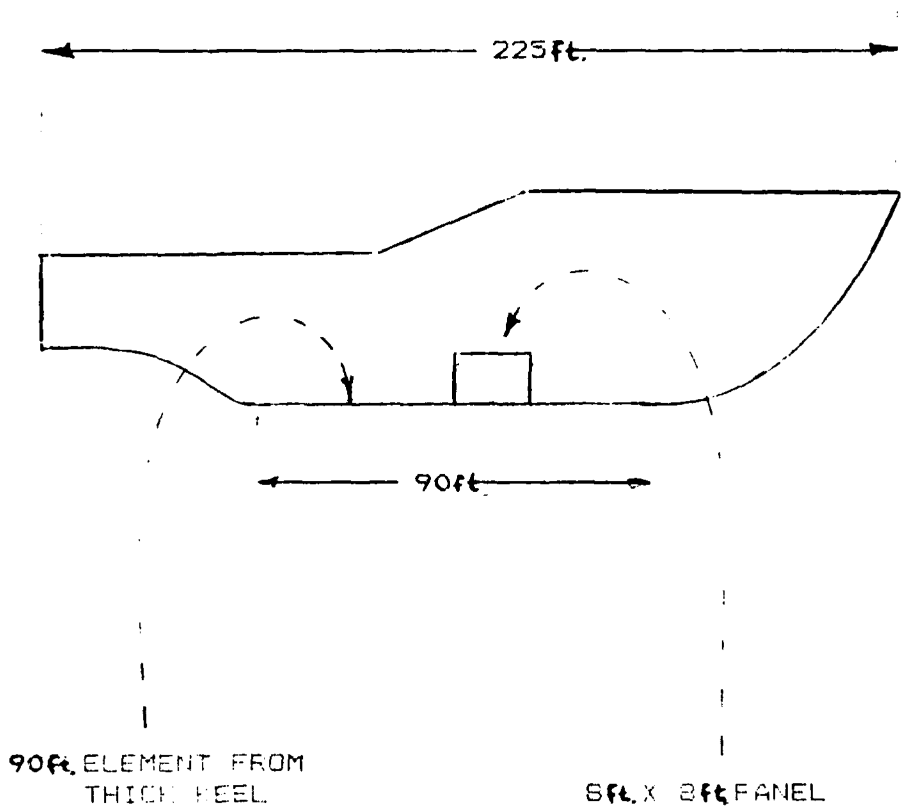
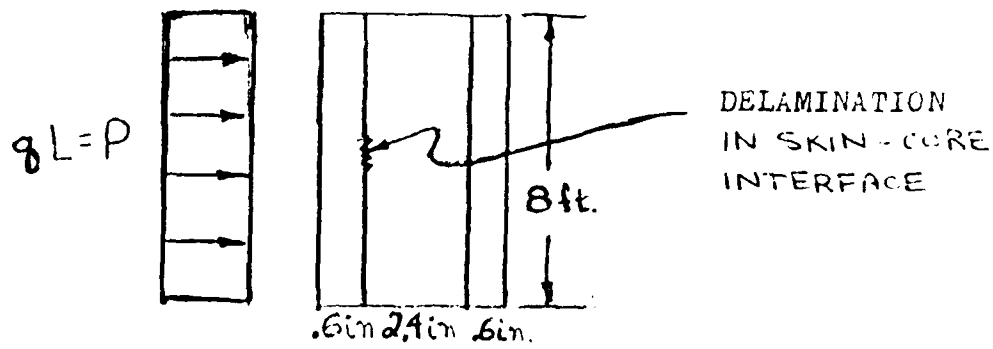


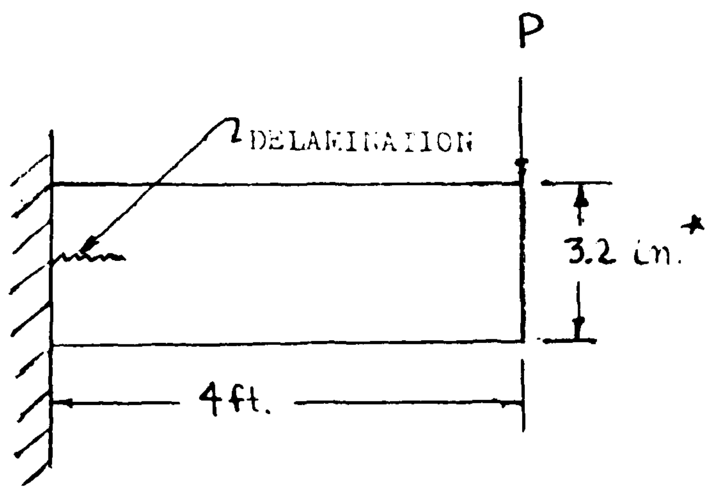
FIGURE 20

MODEL FOR LOCAL LOADING

LOCAL LOADING:



MODEL:



* SEE Appendix F-2 for Solid Beam Analogy Development

FIGURE 34

PROPOSED INSTRUMENTED ROLLER

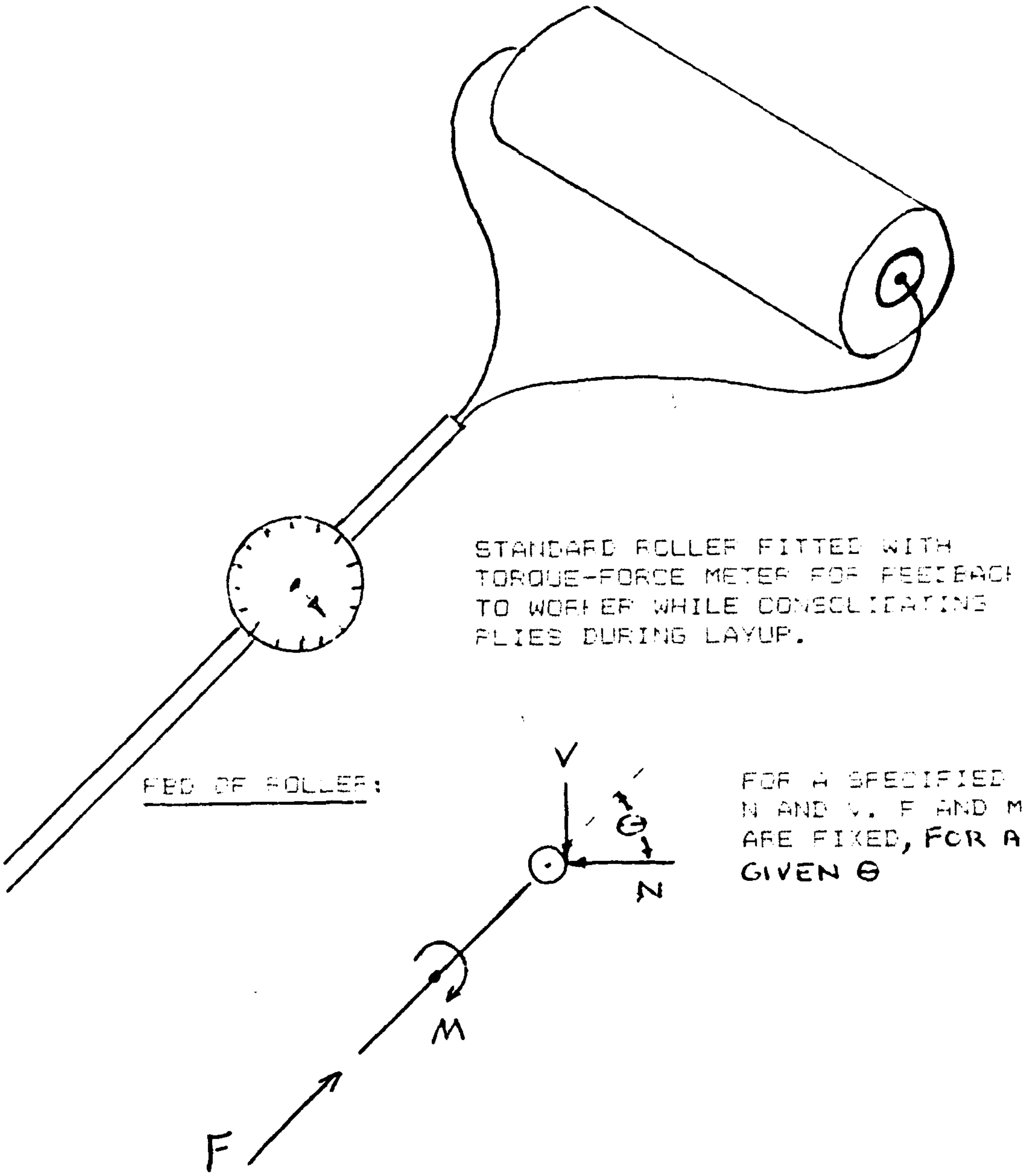


FIGURE 33

LAYUP OF THE LAMINATE USED TO TEST
THE EFFECT OF STAGGERED BUTTED PLY SEAMS

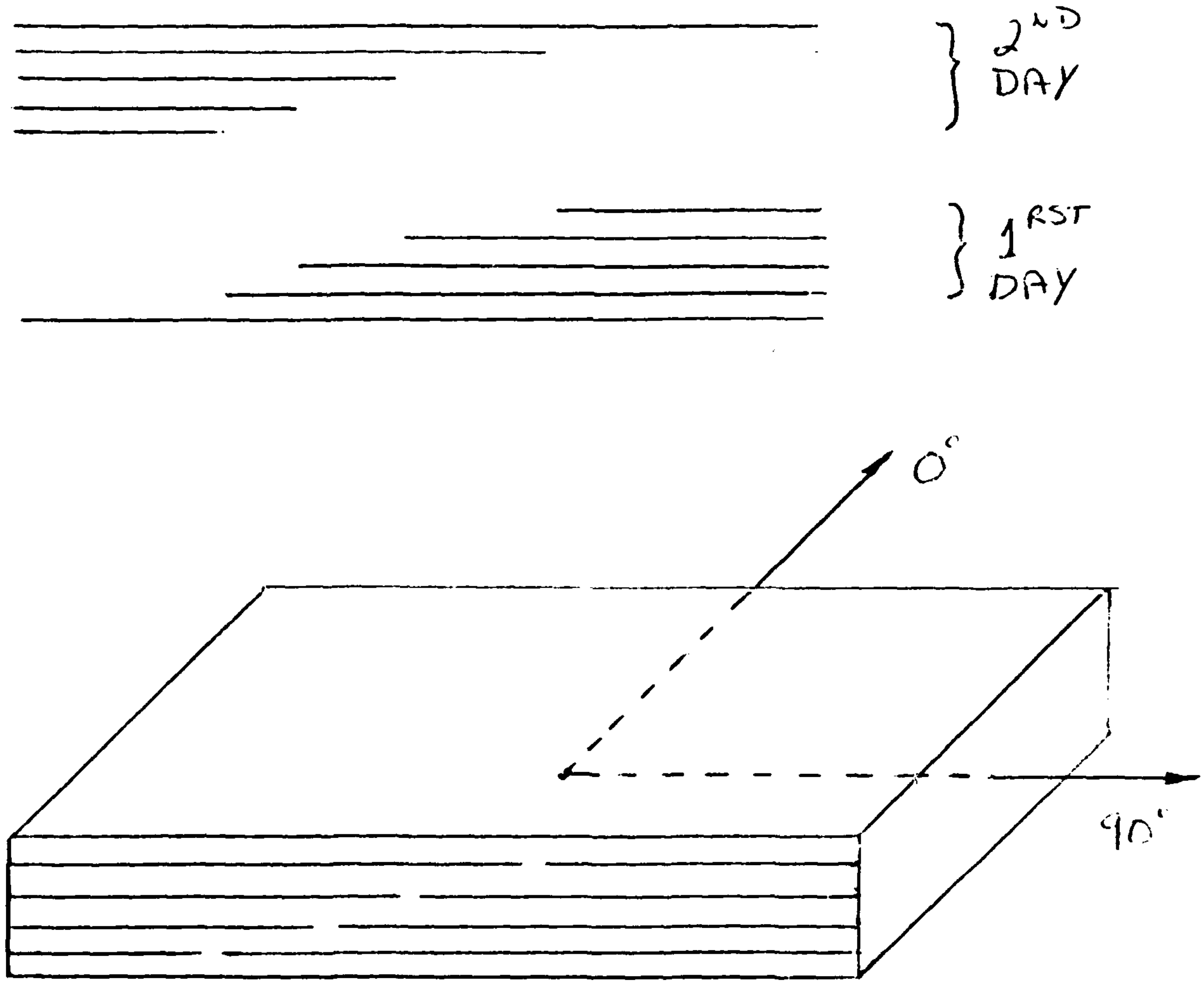


FIGURE 32

LAYUP CONFIGURATION OPTIONS

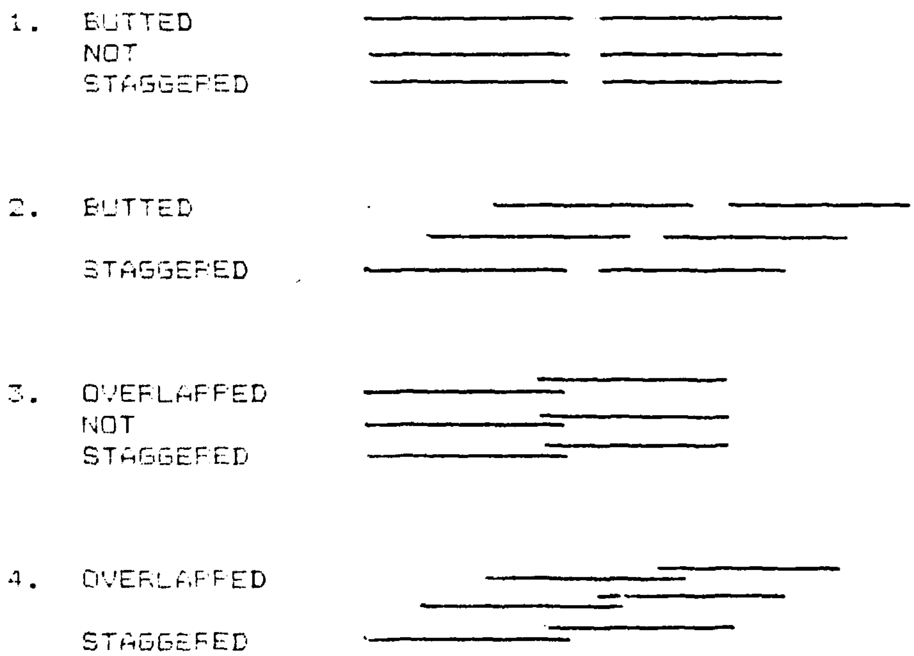


FIGURE 31

RESULTS OF THE HOLE WITH CRACKS MODEL

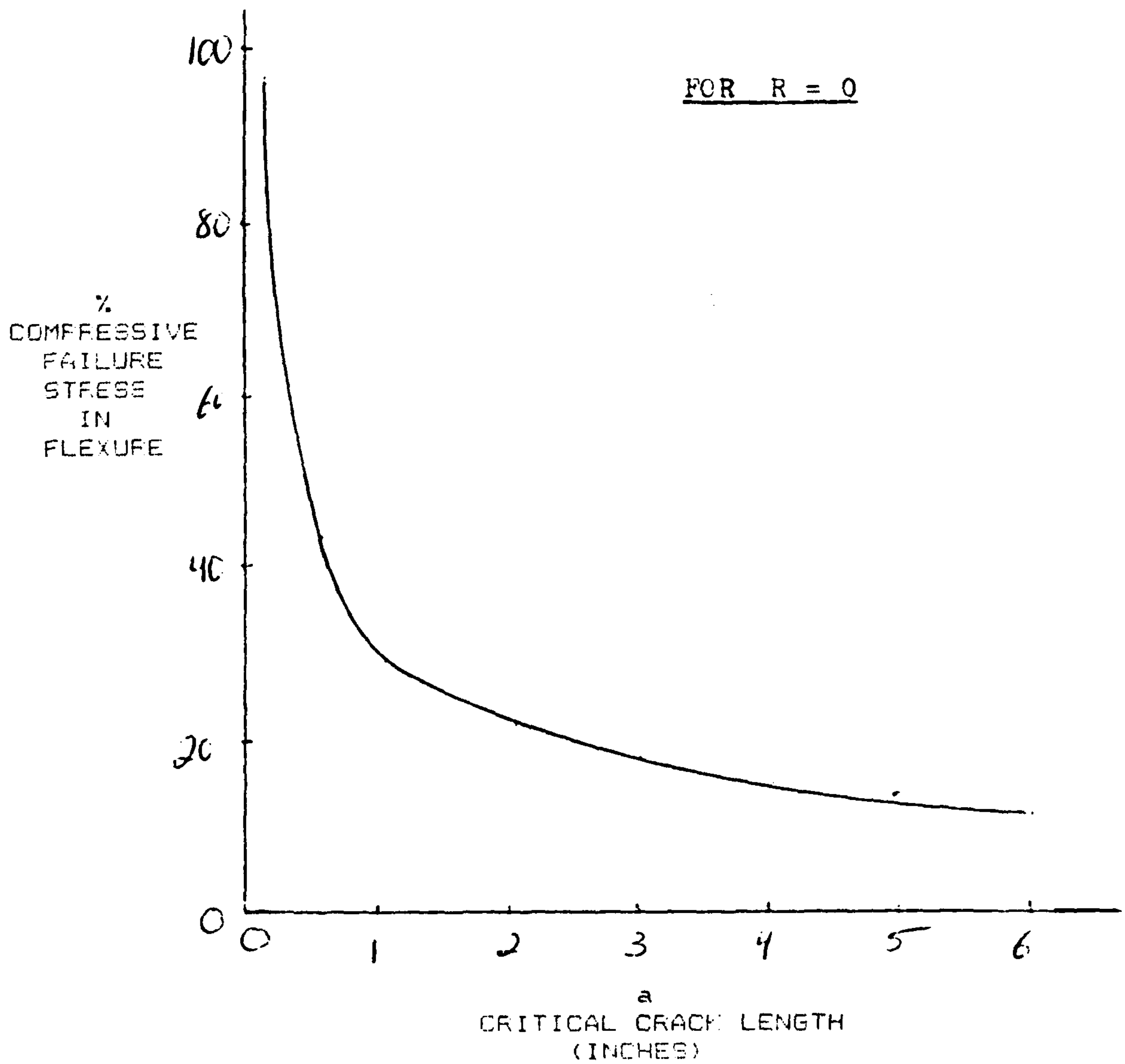
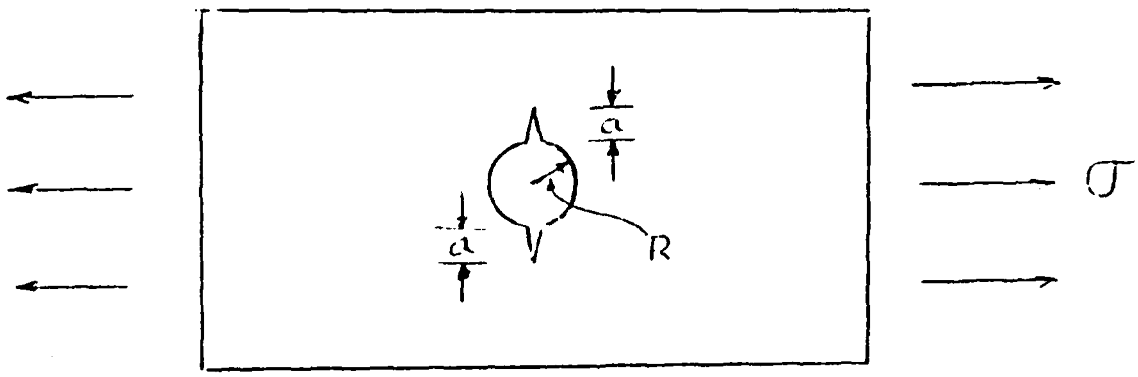


FIGURE 30

DIAGRAM OF CONFIGURATION USED TO
EVALUATE THE EFFECT OF A HOLE WITH CRACKS



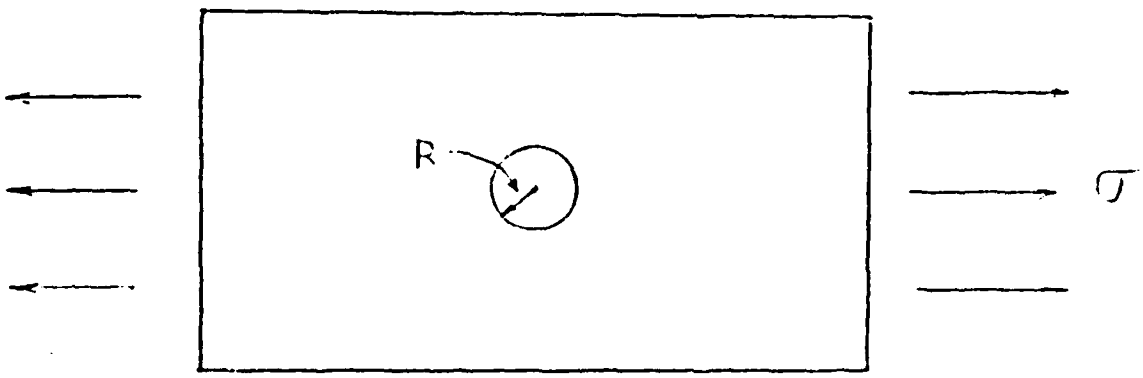
$t = .6$ in.

$\sigma = 2970$ psi

8 ft. x 8 ft. PANEL

FIGURE 29

DIAGRAM OF CONFIGURATION USED TO EVALUATE
THE STRESS CONCENTRATION FACTOR OF A HOLE IN A FINITE PLATE



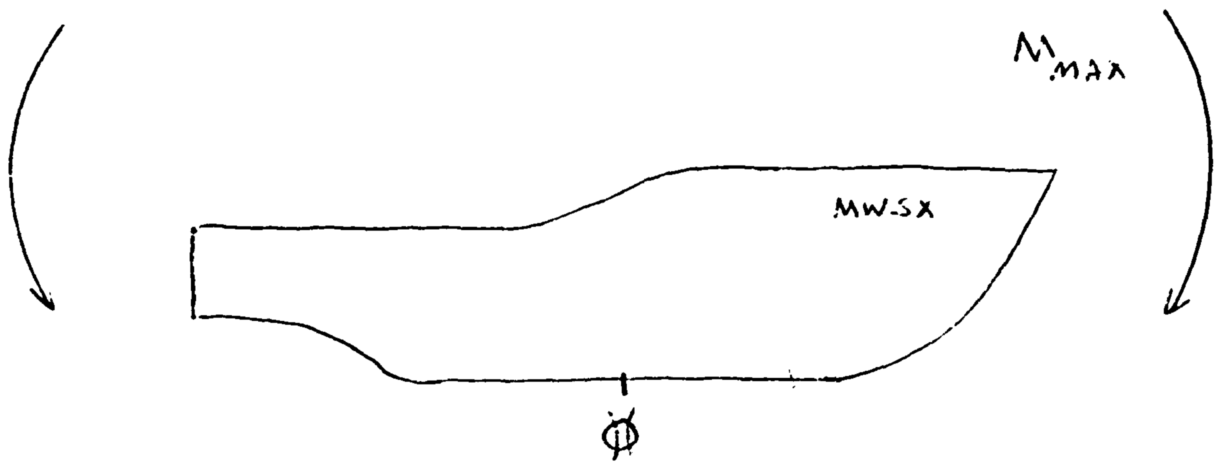
t = .6 in.

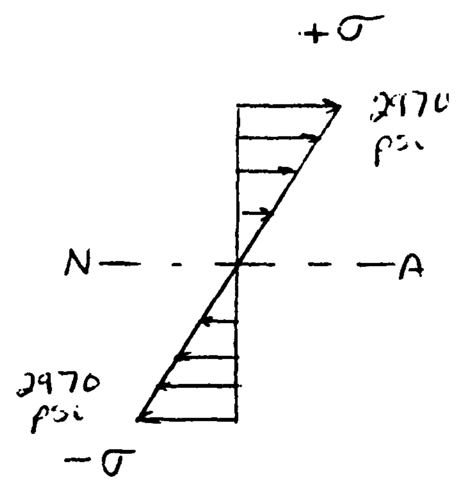
σ = 2970 psi

8 ft. x 8 ft. PANEL

FIGURE 28

ONCE IN 20 YEARS BENDING LOAD





M_{MAX} = 24,615 FT-TONS

Y_{MAX} = 14 FT

I_{ϕ} = 1805 FT^4

$$\sigma = \frac{My}{I}$$

σ_{MAX} = 2,970 psi

FIGURE 27

RESULTS OF
DELAMINATION INDUCED INSTABILITY MODEL

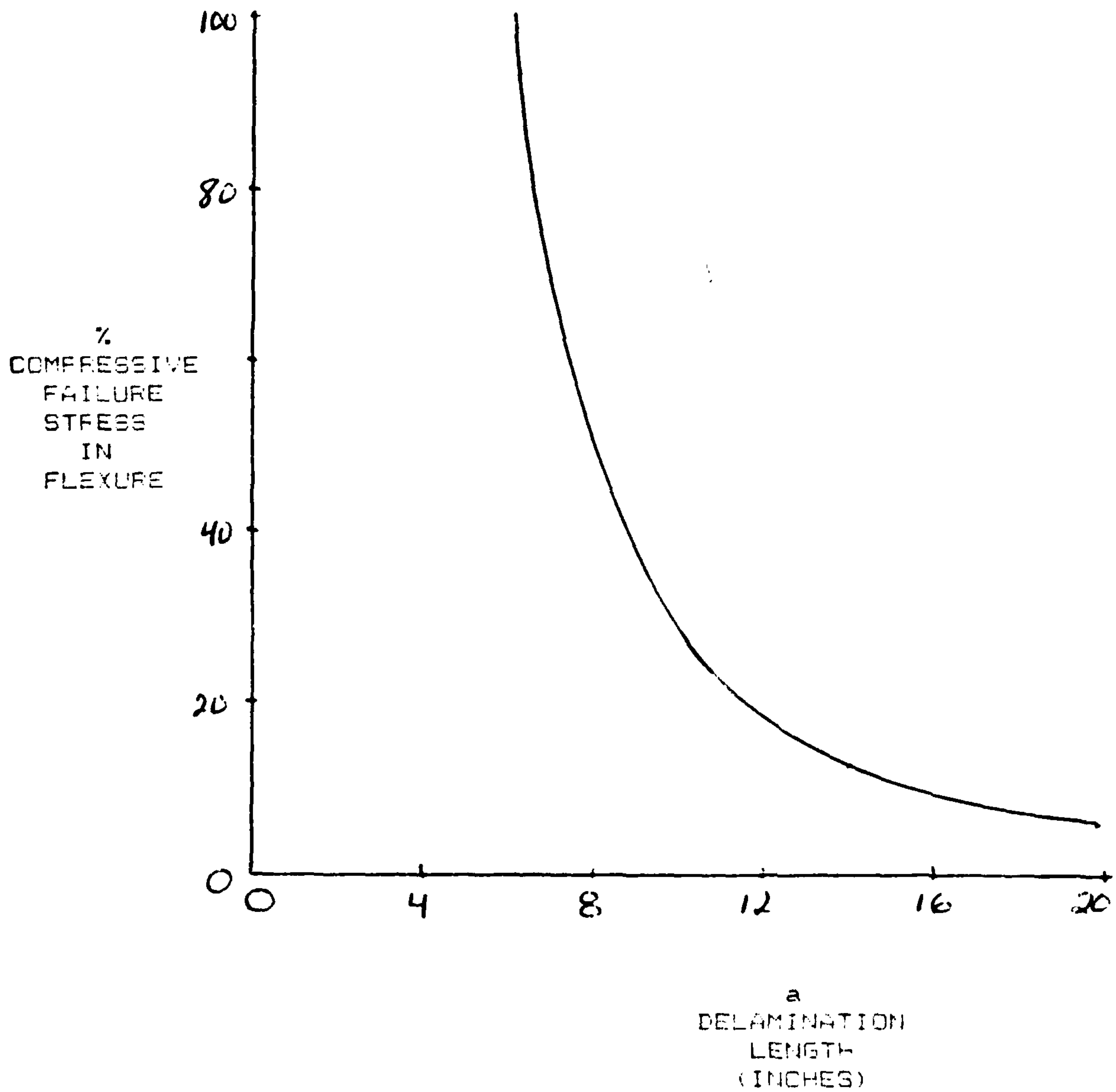


FIGURE 26

DIAGRAM OF INSTABILITY FAILURE DUE TO A CIRCULAR DELAMINATION IN A 3-D PLATE [44]

LOCAL BUCKLING OF A DELAMINATED LAMINATE

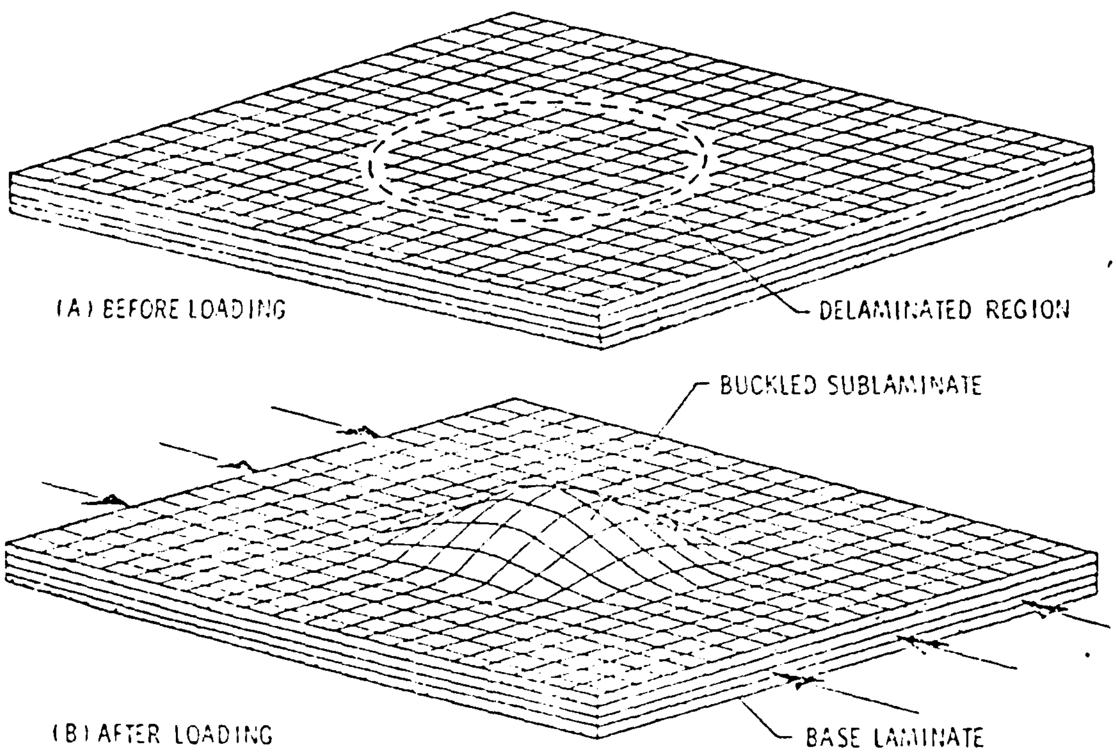
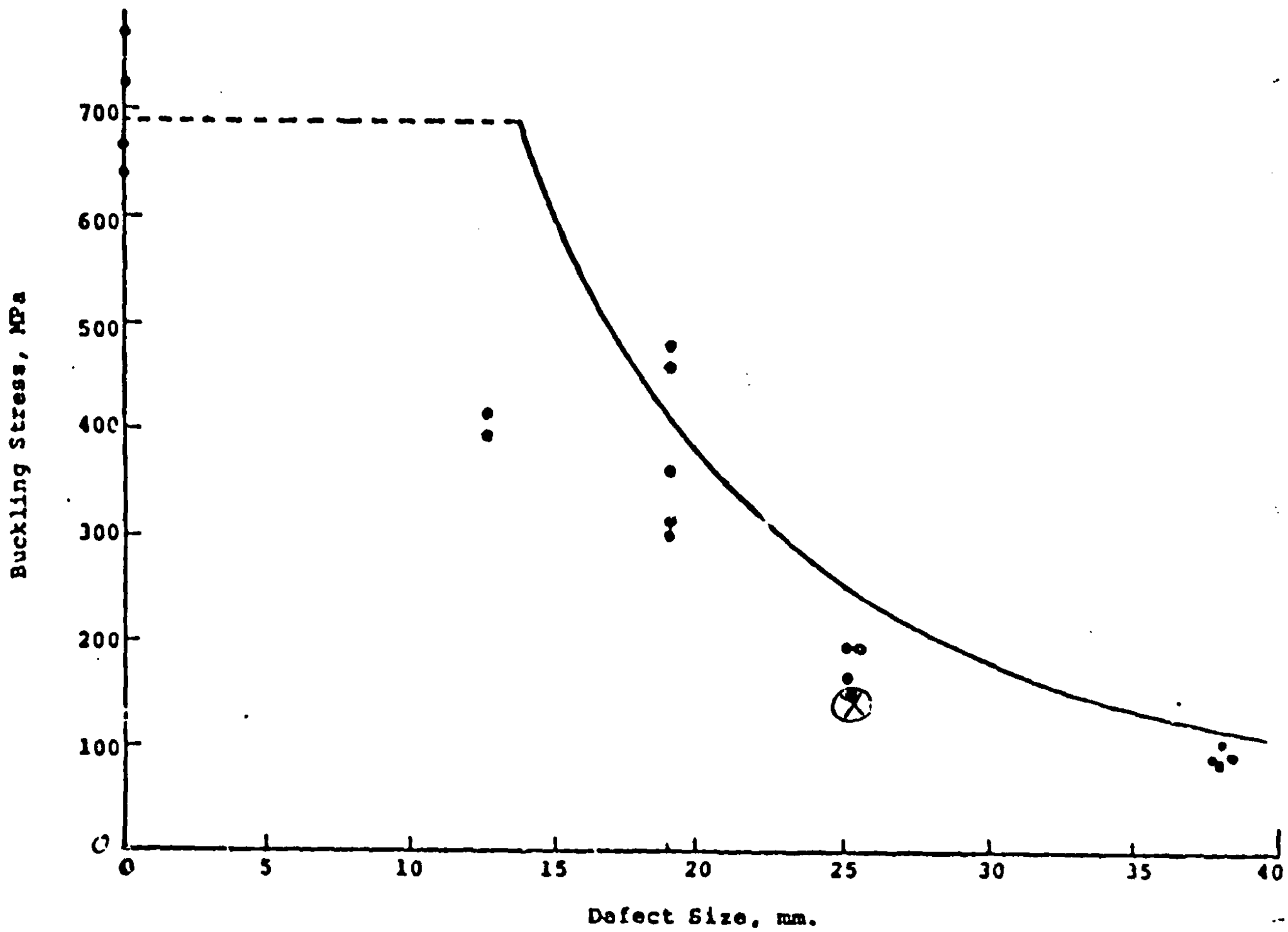


FIGURE 25

DATA CORRELATION FOR INSTABILITY
FAILURE (ANALYTICAL VS EXPERIMENTAL) [43]

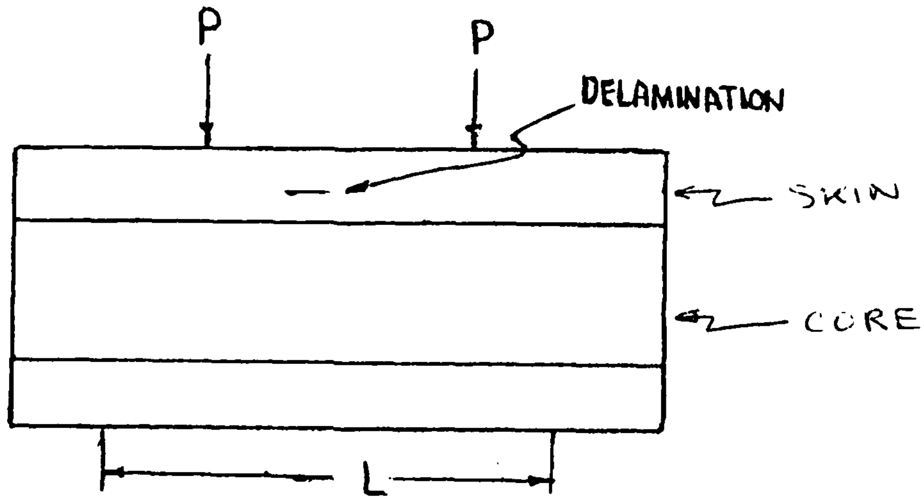


Data Correlation for Buckling Tests

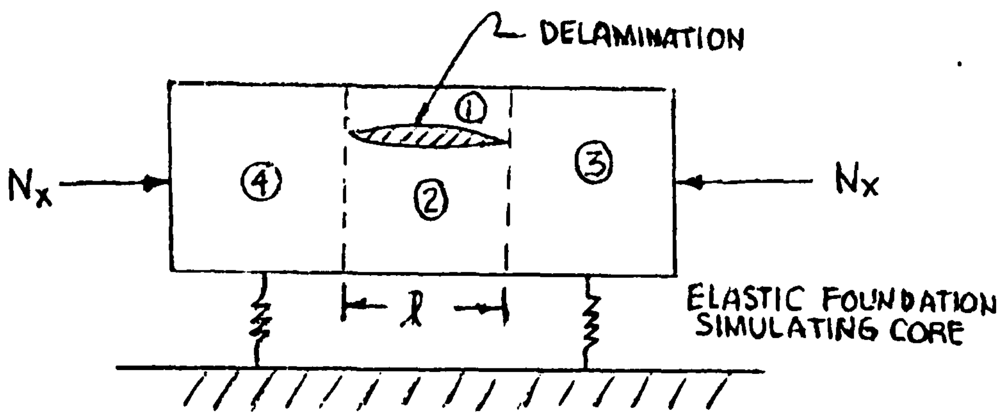
(X) = SIMPLE EULER BUCKLING
PREDICTION FOR A ONE INCH DELAMINATION

FIGURE 24

TEST SPECIMEN AND MODEL
CONFIGURATION FOR INSTABILITY FAILURE [43]



SANDWICH BEAM TEST SPECIMEN WITH
DELAMINATION IN COMPRESSION SKIN



MODEL OF COMPRESSION SKIN WITH DELAMINATION

FIGURE 23

DIAGRAM OF INSTABILITY FAILURE

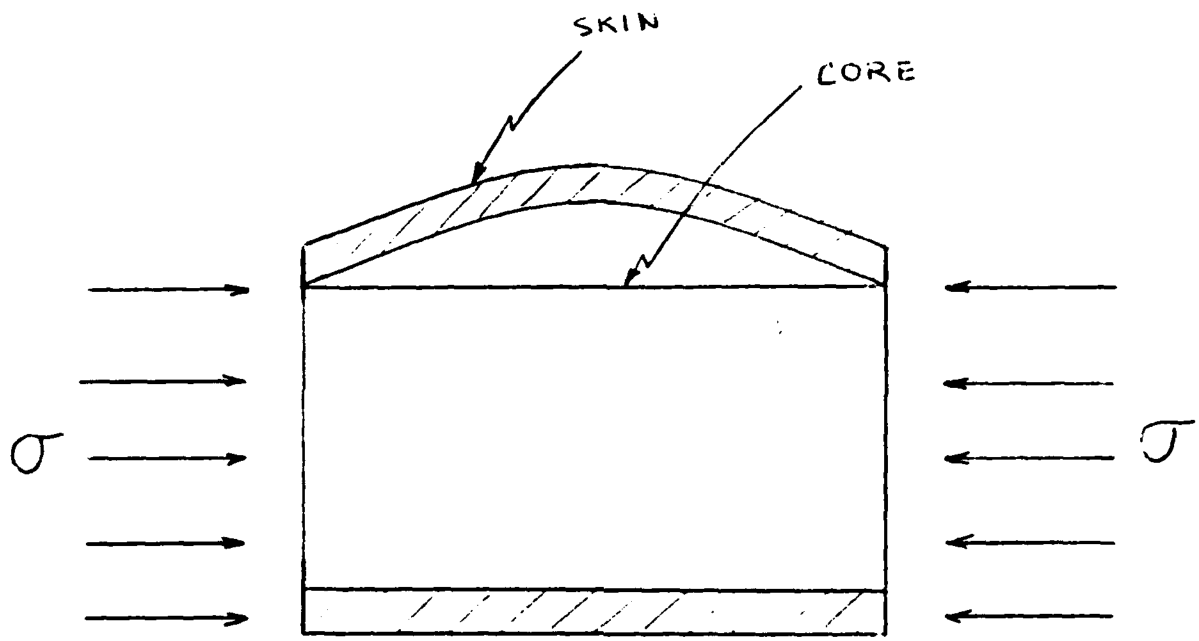


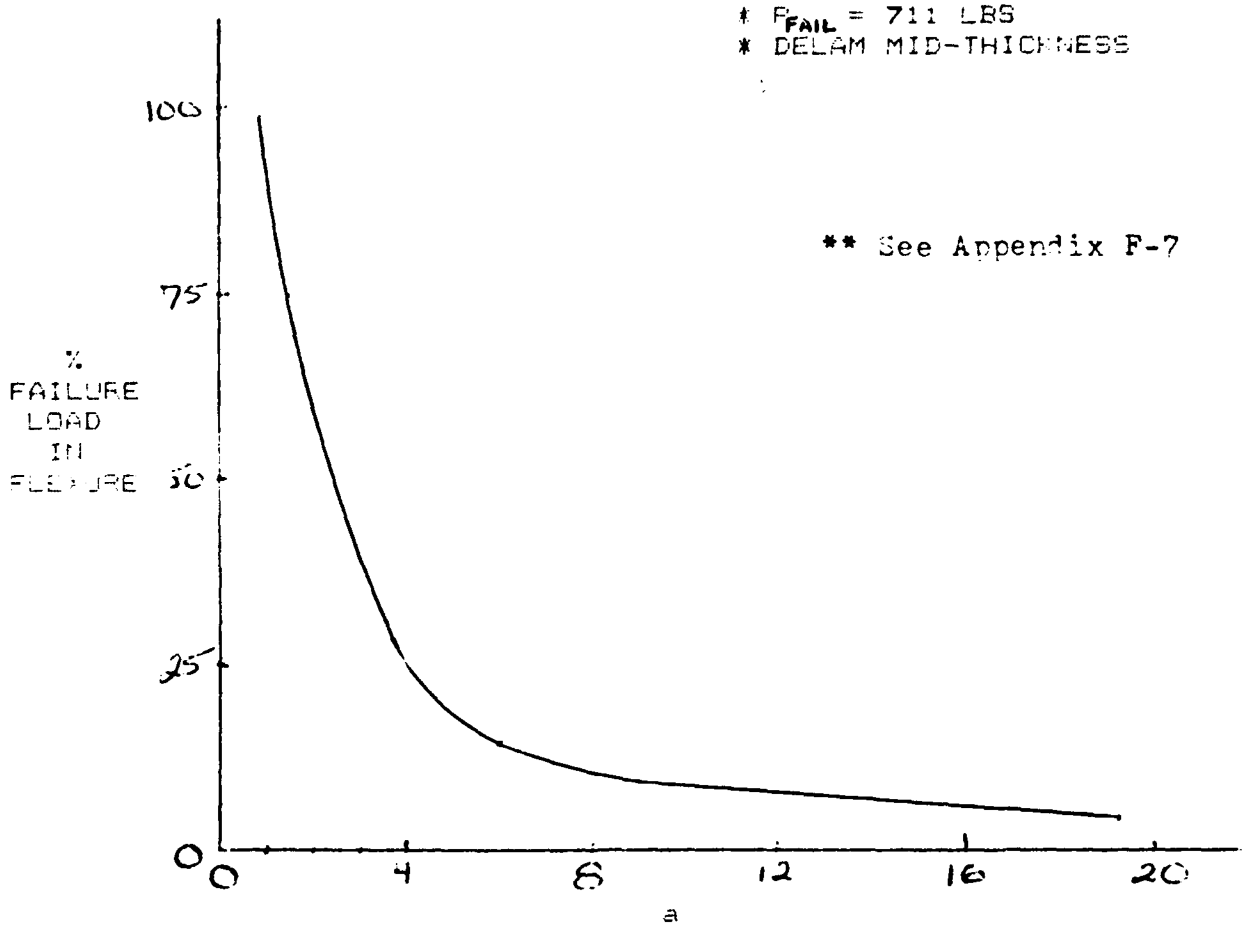
FIGURE 22

RESULTS OF
SHEAR PROPAGATION OF DELAMINATION MODEL

GLOBAL LOADING: $a \geq 59$ IN. CAUSES CATASTOPHIC PROPAGATION **

LOCAL LOADING:

* 8ft. x 8ft. PANEL **
* P_{FAIL} = 711 LBS
* DELAM MID-THICKNESS



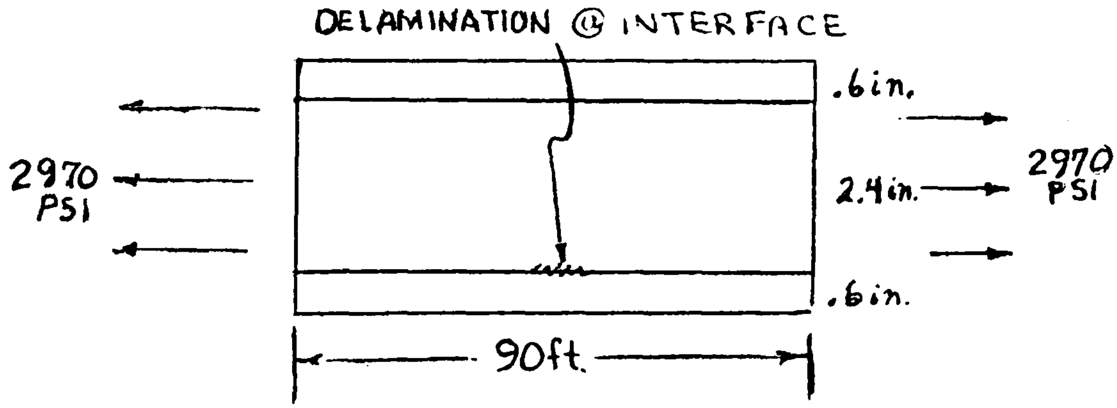
** See Appendix F-7

(Delamination length, inches)

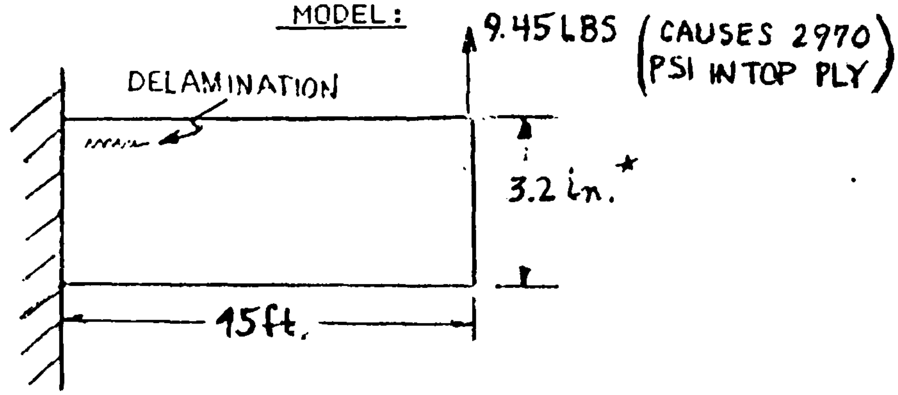
FIGURE 21

MODEL FOR GLOBAL LOADING

GLOBAL LOADING:



MODEL:



Delamination located proportionately same distance from neutral axis

* SEE Appendix F-2 for Solid Beam Analogy Development

FIGURE 35

LOCATION OF TEST TABS FOR DESTRUCTIVE TESTING

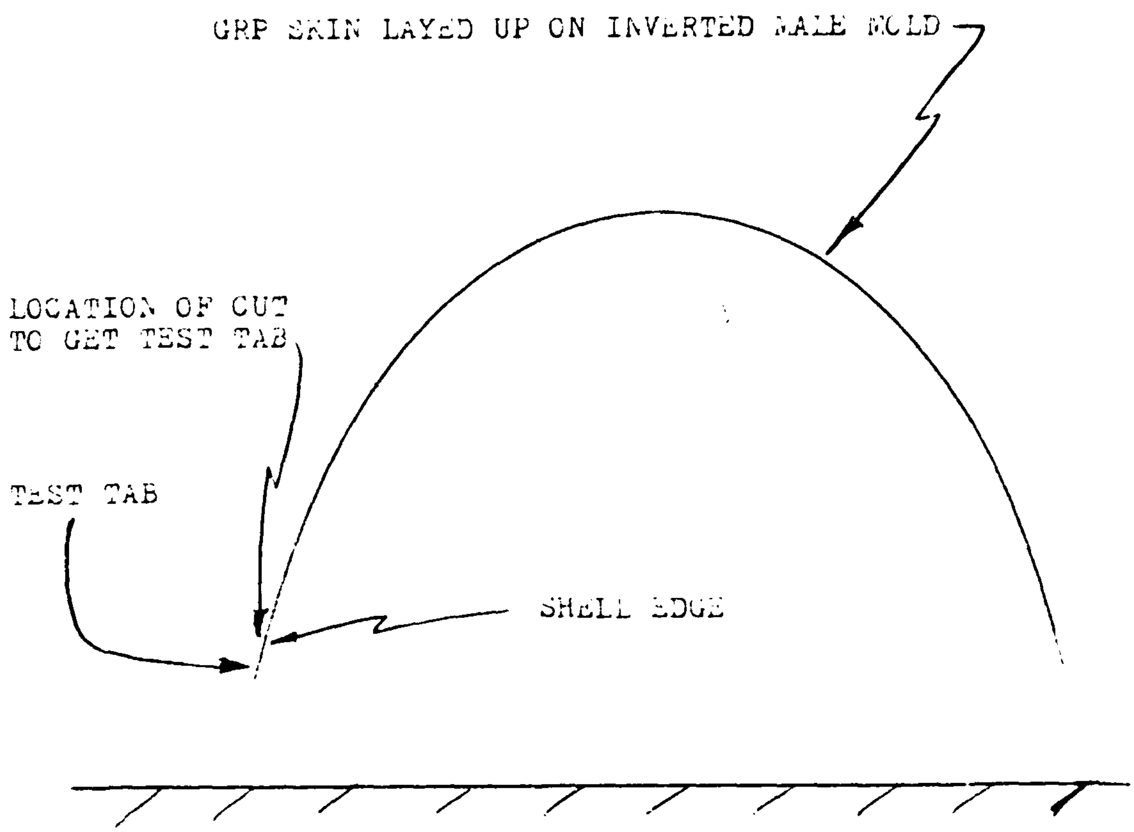
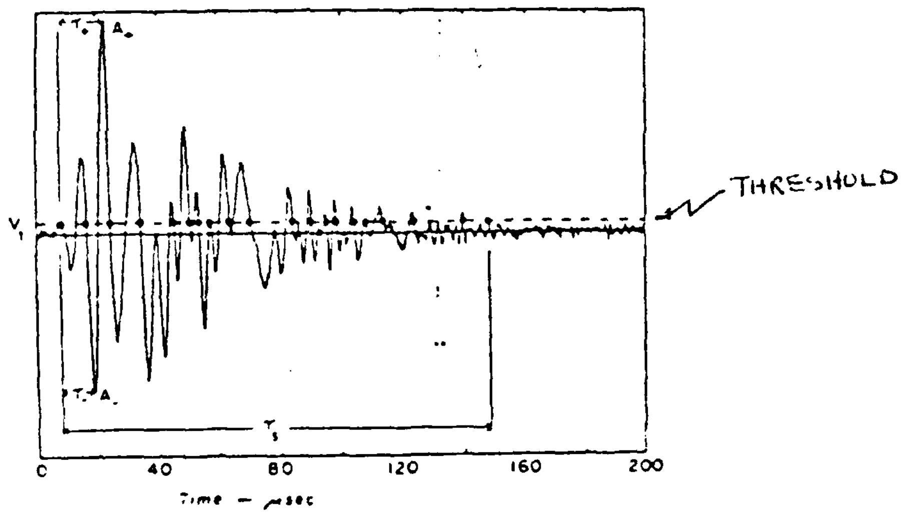


FIGURE 36

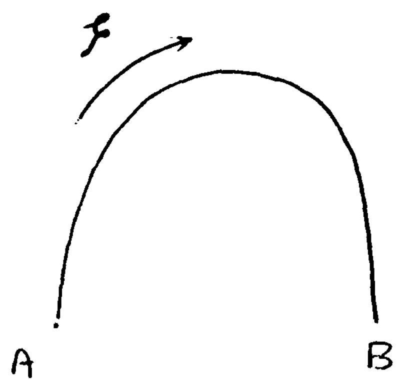
THE ACOUSTIC EMISSION COUNT [61]



Simulated Acoustic Emission Signal Showing the Triggering Points for the Acoustic Emission Count.

FIGURE 37

ARRANGEMENT OF
OPTICAL FIBERS FOR DAMAGE DETECTION



CONTINUOUS PLIES OF
REINFORCEMENT FROM
A TO B ALONG LENGTH
WITH EMBEDDED OPTICAL
FIBERS IN THE f
DIRECTION ONLY

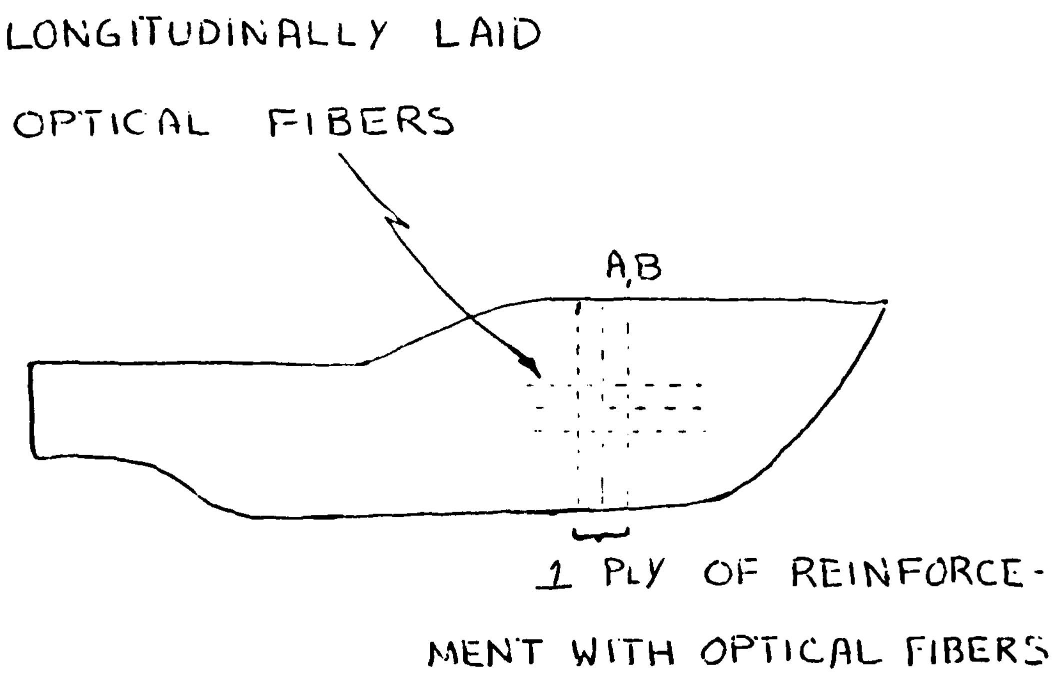
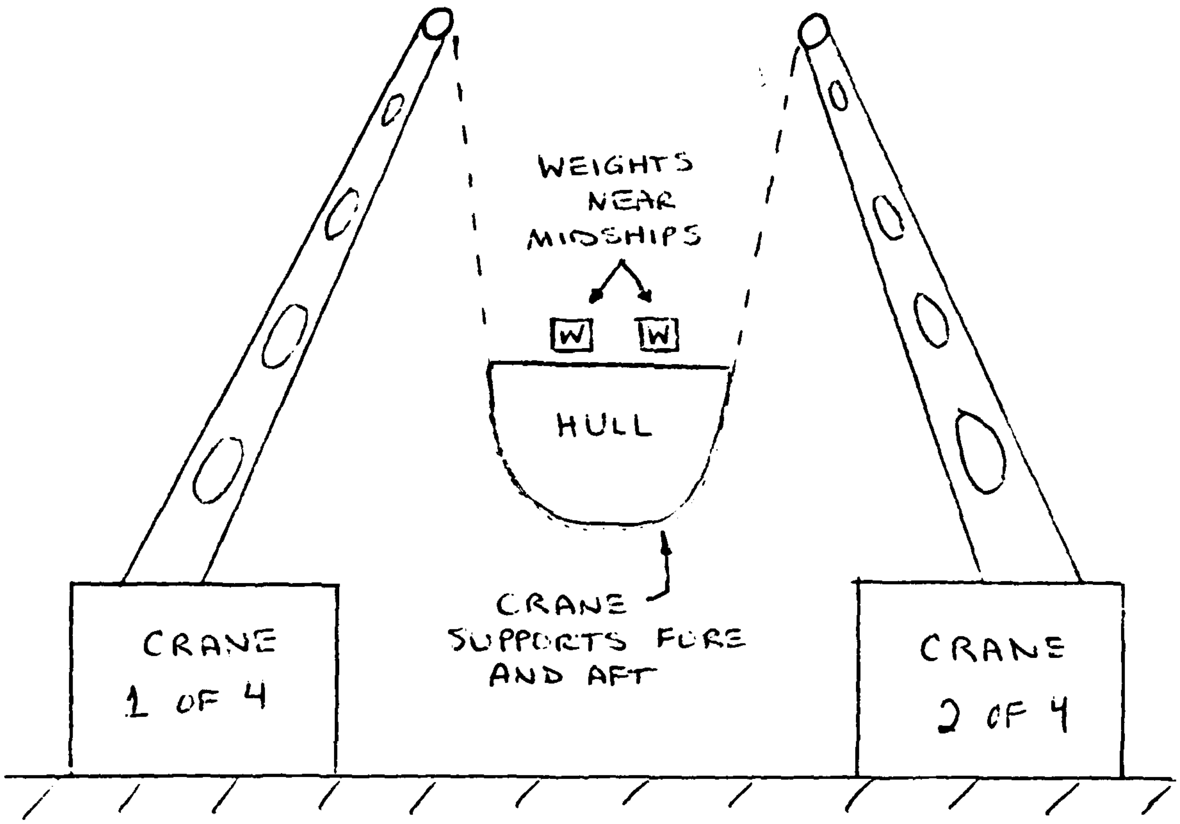


FIGURE 38

ARRANGEMENT FOR BENDING
PROOF TEST OF PROTOTYPE SHIP HULL



APPENDIX A

FACTORS PROMOTING THE USE OF NEW MATERIALS

FACTORS PROMOTING USE OF NEW MATERIALS

- TECHNICAL FACTORS -

PROMOTER	ESTABLISH SYSTEM PERFORMANCE REQUIREMENTS WHICH DICTATE OR ENCOURAGE APPLICATION OF NEW MATERIALS	PILOT LINE DESIGN AND PRODUCTION	USE OF PROTOTYPES UNDER SERVICE CONDITIONS	PROVEN NON-DESTRUCTIVE TEST TECHNIQUES AVAILABLE	UNIQUE MATERIAL CHARACTERISTICS (WHICH MAKE POSSIBLE THE ATTAINMENT OF ADVANCED GOALS) OR A MATERIAL *TAILORED TO MEET* ADVANCED PRODUCT REQUIREMENTS
COMMENT OR ACTION	U.S. is *denying* itself competitive or military advantages by not exploiting new materials attributes. Publish advanced system requirements to encourage development of new materials and manufacturing technology (SST example). Communicate advance needs to materials community.	Demonstrates repeatability of design and production functions. Limited production, test and evaluation of critical components should be encouraged as precursor of larger production runs. Demonstrate readiness to move beyond laboratory & into extensive testing technology development & systems applications.	Exercises design & manufacturing functions, demonstrates practicality of use and builds confidence. Continue to require designs of alternate materials and develop replacement components of new materials for in-service aircraft, adequately instrument and document to insure knowledge acquisition and transmission.	Raises confidence in quality of product, helps assure satisfactory material performance in service. Techniques need be developed for material and product, part and assembly, and in-service quality control.	One or more characteristics are developed to meet the advanced requirement (example: ablative materials). Self-motivating examples: weldable aluminum, beta III titanium for high strength rivets.

FACTORS CONSTRAINING USE OF NEW MATERIALS

- TECHNICAL FACTORS -

CONSTRAINT	LACK OF ADEQUATE DESIGN DATA AND INCREASING NEED FOR MORE COMPLETE MATERIAL CHARACTERIZATION	CHARACTERISTICS DO NOT MEET ALL THE DESIGN REQUIREMENTS	INABILITY TO SPECIFY MEASUREABLE PROPERTIES AND/OR PROCESS PROCEDURES NECESSARY AND SUFFICIENT TO ASSURE MATERIALS THAT CONSISTENTLY MEET SERVICE REQUIREMENTS; INADEQUATE MATERIAL SPECIFICATIONS	INADEQUATE ENVIRONMENTAL SIMULATION AND LACK OF ACCELERATED TEST METHODS	MATERIAL AVAILABILITY	INADEQUATE FABRICATION KNOWLEDGE	INADEQUATE COMMUNICATION BETWEEN MATERIALS PRODUCERS AND DESIGNERS
POSSIBLE SOLUTION OR ACTION	Identify requisite design data and indicate approximate property values necessary for the intended application. Cite acceptable tradeoffs. Screen candidates. Select only the most promising for complete characterization in order to conserve effort. Design information is not always available where it is needed, thus, effort is needed to communicate design data information to those deciding materials selection. Store, share, review & make available to all, through materials information centers, the accumulated data available.	Identify desirable attributes such as strength characteristics and material interaction and compatibility requirements for material developers. Development needs such as modifications in composition, form or thermo-mechanical treatment to meet hardware requirements should be identified and disseminated.	An essential part of the material development process is the early development of a descriptive material specification including material qualification requirements to assure consistent performance of the material as procured. Review and updating of specifications should be continued on a periodic basis. Determine process parameters, optimize, establish controls, prepare process-oriented specifications. Identify quantitative property characteristics necessary for satisfactory service performance. In conjunction the users and producers establish at least some tentative specifications early in the material development phase.	Development and evaluation of methods to 1) simulate complex service environment and/or 2) predict long-term performance on the basis of accelerated testing. Time dependent phenomena are especially troublesome, such as corrosion, elevated temperature behavior, and fatigue. Improve means, analytical and experimental, to maximize information acquired from tests and assure applicability to production hardware.	Emphasize early change-over from pilot plant to production. Users should provide guidance on materials, forms, quantity, sizes, etc., estimated to be required. Develop multiple sources of supply and establish standards of quality. Combine user orders to increase production quantities.	Provide through existing DOD information center activity, for more extensive collection and dissemination of production fabrication technology information. Establish active fabrication methodology development organizations under DOD and NASA that sponsor development of fabrication processes for new materials. Encourage the early involvement of manufacturing personnel in R&D programs & in establishing process specifications.	Emphasize wide dissemination of processes and instructions for design applications. Encourage communications between materials producers and potential users by including them in advance planning teams.

FACTORS CONSTRAINING USE OF NEW MATERIALS

- ECONOMIC FACTORS -

CONSTRAINT	HIGH MATERIAL COSTS UNCERTAIN MATERIAL COST PREDICTIONS	HIGH FABRICATION COSTS UNCERTAIN FABRICATION COST PREDICTION	SHORTAGE OF RESOURCES AND PRODUCTION FACILITIES AND LACK OF FIRM ORDERS CONTRIBUTE TO EXCESSIVE DEVELOPMENT TIME	SIZE AND AMOUNT OF MATERIAL REQUIRED TO EVALUATE FOR USE, AND TO BE ACTUALLY REPRESENTATIVE OF SIZE TO BE USED, CAN BE COSTLY FOR PRODUCER (I.E., REQUIREMENT FOR HEAVY ALUMINUM PLATE)	LACK OF FACILITIES FOR MATERIAL PRODUCTION AND HARDWARE FABRICATION
POSSIBLE SOLUTION OR ACTION	Material producer should be encouraged to lower material costs. Nonaerospace uses of materials should be sought to broaden usage base. A good predictive method or sound estimate on future anticipated cost trends would help the system planner in his forward planning. Material information centers should establish a good historical base of costs and disseminate information regarding improved estimating techniques. Overcome cost-volume bottleneck by increasing usage volume through contractual incentives.	Improved and novel approaches to tooling and manufacturing methods by development contracts or incentive clauses in systems contracts.	Creation of sources, facilities and demand in advance of production requirement seems only way to attack this constraint. A joint industry, user, government planning activity appears necessary. Joint programs to establish capability such as giant press, special extrusion facilities, and equipment pools, in advance of need are warranted.	Potential users should aid producers to establish use parameters for new materials, shapes, or forms. The government may find it necessary to support initial parameters determination where large quantities or sizes beyond producers' resources are involved.	If benefits from use offset facility cost this is self-motivating. Commitment of funds for pilot size trials. Contractual inventives or rapid recovery through tax adjustment for special facilities for new materials. Encourge the development of universal machines such as digitally guided tape layers, large presses, by government funding or fast tax writeoffs.

FACTORS PROMOTING USE OF NEW MATERIALS

- ECONOMIC FACTORS -

PROMOTER	A SIZEABLE MARKET AND ACCEPTABLE RAW MATERIAL COST	AVAILABLE FACILITIES	A MATERIAL THAT PROVIDES AN ECONOMIC ADVANTAGE OR IS UNIQUELY CAPABLE OF MEETING AN ESSENTIAL REQUIREMENT: I.E., COMPETITIVE ADVANTAGES AND PROCUREMENT	MULTIPLE SOURCES OF SUPPLY AND MULTIPLE FORMS
COMMENT OR ACTION	The aerospace market continues large; however, corollary uses of aerospace materials in other trades should be sought out and encouraged by communications and experimental demonstrations, to increase market base, reduce unit costs and improve revelance. Use of new material is accelerated when material costs are acceptable or advantageous on a cost effective basis.	Pooling of tools, development of adaptive complimentary tools such as universal tape laying equipment in composites industry.	Self-motivating by cost-effectiveness or performance gains.	Material "availability" assures adequate basic supply on schedule. Tend to reduce raw material cost and potential program schedule impact costs.

FACTORS CONSTRAINING USE OF NEW MATERIALS

- CONTRACTUAL FACTORS -

CONSTRAINT	THE WEAPON SYSTEM PROCUREMENT SPECIFICATION DESCRIBES AN ITEM WHOSE PERFORMANCE REQUIREMENTS CAN BE MET WITHOUT USE OF NEW MATERIALS. SINCE NEW MATERIALS ARE GENERALLY LESS ATTRACTIVE FROM COST, AVAILABILITY, RELIABILITY, OR *SIMILAR VIEWPOINTS, THIS INHIBITS* THEIR CONSIDERATION EVEN THOUGH SUCH USAGE MIGHT BE ADVANTAGEOUS FOR FUTURE SYSTEMS	UNILATERAL RISK BY CONTRACTOR, PARTICULARLY IN FIXED PRICE CONTRACTS	CONTRACTUAL REQUIREMENTS AND COMPETITIVE ENVIRONMENT DEMAND MULTIPLE SOURCES FOR MATERIALS. CAN CONSTRAIN USE IF MATERIAL IS PROPRIETARY
POSSIBLE SOLUTION OR ACTION	Contractual relief of the manufacturer/designer from penalties incident to new material usage. Contractual requirement or incentive to use new materials. Risk taking should be encouraged, especially where human life or essential system functions are not endangered, or where the potential gain offsets the hazard involved.	Increased incentives in systems contracts for effective utilization of new materials. Recognizing value of increased performance for defined increments such as range and speed, by contract incentives.	Incentives for multiple sources must be established, perhaps by subsidy, or special contractual arrangements. Relax contractual requirement on items scheduled for limited procurement.

FACTORS PROMOTING USE OF NEW MATERIALS

- CONTRACTUAL FACTORS -

PROMOTOR	INCENTIVE OR DEMAND CLAUSES: LEGALLY THERE IS PROVISION FOR GREAT FLEXIBILITY IN MILITARY CONTRACTS	COMPREHENSIVE CONTRACTUAL COST ANALYSIS
COMMENT OR ACTION	A form of contract which provides a schedule of incentives for performance greater than contract minimums could encourage application of advanced materials where specific gains can be achieved.	When judging whether the use of a new material is cost effective, the cost analysis should be based on the initial cost plus the inventory lifetime cost. Some advanced materials have superior corrosion or wear characteristics and will require less maintenance. This should be considered in the selection procedure. Present contract cost analyses appear to consider only material and manufacturing costs with very limited considera-tion of system employment costs.

FACTORS CONSTRAINING USE OF NEW MATERIALS

- MANAGEMENT AND ORGANIZATION -

CONSTRAINTS	MANAGEMENT CONCERN OVER THE RISK OF BEING FIRST TO USE A NEW MATERIAL BECAUSE OF HIGHER COSTS, QUESTIONABLE AVAILABILITY, ETC.	MANAGEMENT LACK OF CONFIDENCE BECAUSE OF INSUFFICIENT PROPERTY KNOWLEDGE, LACK OF ASSURANCE AGAINST DEFICIENCIES AND LACK OF ASSURANCE OF PRODUCTIBILITY	MANAGEMENT CONSIDERS GAINS ARE INADEQUATE BECAUSE SYSTEM SPECIFICATIONS, COST ESTIMATES AND DESIGN CONCEPTS ARE BASED ON OFF-THE-SHELF MATERIALS
POSSIBLE SOLUTION OR ACTION	Provisions in contract to encourage or incorporate backup programs. Solution is to extend material development effort beyond what has been normal practice. Recognition of risk factors in contracts.	This constraint can be solved through expansion of our knowledge base by prototype programs, pilot line operations and experience acquisition.	Provide incentives in contracts which encourage new material exploitation. These might take form of premium allowable costs for new material use and/or added financial gains for improved system performance increments.

FACTORS PROMOTING USE OF NEW MATERIALS

- MANAGEMENT AND ORGANIZATION -

PROMOTER	PATRIOTISM–THE NATIONAL DRIVE TO DISCOVER, DEVELOP AND CONSTRUCTIVELY APPLY INCREASING KNOWLEDGE AND TECHNICAL CAPABILITY AS AN INTEGRAL ELEMENT OF NATIONAL STRENGTH AND WELL-BEING	NATIONAL EMPHASIS ON NEW MATERIAL APPLICATIONS AND EXPLOITATIONS	LONG-RANGE PRODUCT PLANNING TO DETERMINE AND INSPIRE ADVANCED MATERIAL CHARACTERISTICS DEVELOPMENT	TOTAL SYSTEMS APPROACH–R & D, DESIGN, MANUFACTURING, SERVICE ENGINEERING, ETC., ALL APPLIED TO USING A NEW MATERIAL IN A PRODUCT
COMMENT OR ACTION	An intangible but real motivating force of our American system that needs to be encouraged on a national scale thru activities of universities, non-profits, and government agencies.	Establish a concerted and continuing effort on a national scale to maximize and accelerate near-term utilization of new materials perhaps by assignment of responsibility to a national agency. Definition of objectives for development of new materials for the next 5, 10, 15 years should be the highest priority assignment. Establish and maintain a consistent and continuing management commitment, whether government or industry, to a total plan to develop and utilize a new material for advantages which will accrue.	Foster long-range coordinated planning by producers, systems manufacturers and government agencies to discover and establish the needs for and potential rewards of new material development. Feedback to material developers is essential.	Identify and recognize the total near- and far-term advantages of new materials applications to systems, i.e., performance advantages, serviceability advantages, etc. Avoid uncoordinated proliferation and application of new materials by establishing and maintaining technical communication between producers, manufacturers, and government agencies.

APPENDIX B

INSPECTION PLAN FOR HULL GRP SANDWICH

APPENDIX C

MINE WARFARE SHIP (MWSX) SUMMARY

The MWSX (Mine Warfare Ship Experimental) is a keel up feasibility design performed by the authors. This effort represents the culmination of a year long senior design project, M.I.T. course 13.461, that is an integral part of the Ocean Engineer program within the Department of Ocean Engineering for U.S.Navy Officers at MIT.

The MWSX is used as the example of an advanced naval vehicle in the text of this thesis. An advanced naval vehicle can be generally characterized by a low factor of safety in its structural design.

Pertinent information about the MWSX is included here:

Mission:	Minesweeping and Mine nuetralization
Environment:	All oceans of the world; actual mine neutralization activity in coastal waters
Characteristics:	Length---------225ft. Displacement---1400 tons Beam-----------44ft. Draft----------10.8ft Depth----------28ft.
Hull design:	The hull is a sandwich material. The faces are combination plies of woving roving stiched to chopped strand mat (total weight 58 oz/sq yd) in a polyester resin. The core is a high performance, high density (15.6 lbs

INTENTIONALLY BLANK

4 FINAL INSPECTION

All items produced are visually inspected.

Trapped air, in the form of small bubbles in the completed laminate, must not exceed 3 % in roving laminate and 4 % in mat laminate of the volume under any surface area of 1 m^2. No single air bubble greater than that encircled within a diameter of 15 mm is permitted. Faults such as delaminations, surface pores, cracks, poorly wetted reinforcement, accumulations of pure resin, orange peel finish or other surface defects are not acceptable. Defects are to be removed according to the inspector's instructions and the laminate is to be repaired to make it free from faults and qualitively comparable to adjacent laminate.

Classifications and estimations of laminate defects e.g. air enclosures and delaminations are based on the principles of "Inspection Manual for Fibrous Glass Reinforced Plastic Laminates" (Navships 250-346-2), Wash. DC., 1964.

The inspection is documented.

Before starting laminating the inside of the hull, the ships centerline is obtained and full and half widths are measured. Five equally spaced points are inspected. The results are documented and presented to the design engineer in charge for his approval before starting laminating the inside.

3.4 QUALITY TESTING

All outcuts shall be identity marked.

Material testing:
Test blocks from finished structure:

Test block	marking
Hull (VS-hole)	4170-117294
Deck	4170-7403
Bulkhead (door)	4170-116767
House (door)	4170-117327

Tests to be performed:
Glass content, tensile ultimate strength, E-modulos for the laminate, bonding and bending for complete sandwich structure.

The Inspection Department, Tc, is responsible to identify test material, order proper tests and report the obtained results.

Inspections performed are signed off in the production logg book.

Gel time is checked weekly. Tests to be performed in current production.
Checks performed are signed off in the production logg book.

To continue laminating after interuption, following shall be considered:

A Interuption less than 24 hours: If necessary clean the surface by use of styrene.

B Interuption max 20 days or the Barcol hardness max 40 units: Clean the surface by use of styrene, grind with paper and clean from grinding dust.

C Interuption longer than 20 days or the Barcol hardness greater than 40 units: Clean the surface by use of styrene. Grind with rough paper and clean with a great quantity of styrene.

The client's representative is called for his approval of completed lamination.

3.: DIMENSIONAL INSPECTION

Assembly of rib frames
Every 5th frames are checked regarding full and half widths, heigth and DWL.

The rib mould are inspected regarding:

Alignment
Frame spacing
Total length
Fairing

The client's representative is called for his approval.

Laminating
Before turning the hull over, the DWL is transferred to the outside of the hull. Six drilled holes are used. After turning over, the hull is levelled to the DWL.

Use of chopped strand mats acc. to KVS 1296 and laminating acc to DWG 9000-212357.

Rec.value	30-32 %
Min	28 %

Thickness measurements by use of ultrasonic testing:

Instrument: Panametrics 5227 or similar
Calibration blocks of same material as testmaterial.

Number of tests:

Hull (in- and outside)	20
Bulkheads, decks	60
House	20

Tests are performed at finished laminates before polyester coating. Locations and results are documented.

On completion of each layer the following shall be inspected:

Air bubbles
Delaminations
Bonding faults
Wrinclers
Running
Cracks
Pores
Deformations
Protruding glassfibres
Taperings

Fully completed laminates are to be inspected as above plus the following:

Surface finish
Surface smoothness
Hardness after 20 days

PROCESS INSPECTIONS

1 Coring

When coring, inspection of core density by colour codes according to KVS 1038. Performed by the shop personnel.

Prior to filling, inspection of joint preparation.

Joint fillings are visually inspected and tested by use of test specimens, core plugs, one per 200 m bonded joint. The specimens are identity marked and registered in the production logg book by location (hull, bulkhead, deck etc), result and, if applicable actions taken. Positions are indicated on the hull drawing. The specimens are visually inspected.

The uniformity of the core is inspected througout construction. Adjustment fillings of glue joints, filling of nail holes etc and grindings are inspected by the Inspection Department, Tc.

The client's representative is called for his approval prior to starting laminating.

2 Laminating

Spot checks of glass content:

Number of tests	
Hull (in- and outside)	10
Bulkheads, decks	30
House	10

Tests are performed random during the laminating phase. Test specimens' locations are documented on the hull drawing.

Glass content requirements:

Use of combi sheetings all to KVS 1297 and laminating are to DWG 9000-212357:

Rec. value	40-42 %
Min	38 %

3 PRODUCTION INSPECTIONS

3.1 PRODUCTION LOGG BOOK

The Inspection Department, Tc, prepares the production logg book. All inspections and tests performed shall be noted in the logg book by the inspector. All structural laminations shall be booked. Starting time, terminating time, etc. are booked by the workshop personnel. RH and temperature etc. by the workshop personnel.

The production logg book shall be available for review of the client's representative.

All KkrV quality documentation shall be included in the logg book.

After finished work, the Inspection Department, Tc, shall keep the logg book in a permanent file.

3.2 PROCESS CONTROL

Work with the plastic is to be carried out preferrably in the temperature interval 18-20°C but not below 15°C.

Surfaces to be laminated shall have a temperature at least 4°C above the dew point.

Premises are to be kept free from oil, grease and water and, as far as practically, free from dust and dirt.

Remains of glass fibre material, intended for later use are to be immediately placed in the area reserved. Unusable remains are to be disposed.

ENVIRONMENTAL INSPECTIONS

Temperature and RH are to be automatically registered. The Inspection Department, Tc, locates the recorders in the workshop. The graphs are filed by the Inspection Department in the production logg book. The recorder's location is noted on the graph.

The Inspection Department, Tc, performs spot checks of surface temperatures twice a day. Measured surface temperature and dew point are booked in the production logg book.

Glass shall, 2-3 days prior to use, be stored unsealed at approx. +25°C.

All nonconformancies shall be reported to the Inspection Department, Tc.

The Inspection Department, Tc, performs spot checks every four weeks. List of spot checks performed, showing date and signature of the inspector, is filed with the material certificates by the Inspection Department, Tc.

The test certificates are kept in file by the Inspection Department, Tc.

For each charge the Inspection Department, Tc, checks the gel time. The test report is filed together with the certificate.

Prior to delivery of the hull from the plastics workshop the Inspection Department submits a "Certificate of compliance, polyester and filler".

2.3 GLASS

Quality requirements according to KVS 1296 and KVS 1297.

Test certificates shall be included in all deliveries.

The Inspection Department reviews and approves the certificates and releases the material.

The certificates shall show:

Weight
Loss on ignition
Moisture content.

The test certificates are kept in file by the Inspection Department, Tc.

For each delivery batch and type, the Inspection Department, Tc, checks the weight by 1 m material.

Prior to delivery of the hull from the plastics workshop, the Inspection Department submits a "Certificate of compliance, glass".

2.[illegible] STORAGE

The Manager of the Stores, Tdm, is responsible to follow the requirements concerning environmental properties and maximum storage time as stated in KVS for each material.

2 INCOMING MATERIAL

2.1 CORE MATERIAL

Quality requirements according to KVS 1038.

Inspection of core material by the manufacturer according to by Karlskronavarvet AB approved inspection manual and plan.

At receipt of core material, the Quality Assurance Manager, Qa, reviews and approves the quality reports and releases the material.

Copies of test certificates are kept in file by the Inspection Department.

Prior to delivery of the hull from the plastics work shop, the Inspection Department, Tc, submits a "Certificate of compliance, core material".

Verification tests to be performed by a third party authority are specified by the Hull Design Department, Tkf. The Inspection Department, Tc, is responsible to arrange for the required test specimens and to send them for testing. Authority to be used: KTH, Department for Light Structures. Test documentation is filed by the Inspection Department. Copies to Tkf and Qa.

2.. POLYESTER AND FILLER

Quality requirements according to KVS 1035 and KVS 1040.

Test certificates shall be included in all deliveries.

The Inspection Department reviews and approves the certificates and releases the material.

The certificates shall show:

	POLYESTER	FILLER
Acid value	x	
Gel time	x	x
Viscosity	x	x
Exoterm max.	x	x
Density	x	x
Styrene content	x	

GENERAL

This inspection plan is prepared in accordance with the Quality Assurance Manual, Section 12.1.

The plan shows the inspections and tests to be carried out during manufacturing of the GRP-Sandwich hull, ship no..... In the plan, requirements and referrences of quality requirements, are stated.

The Manager of the Inspection Department, Tc, is responsible to follow the inspection plan in all respects and, when found necessary, expand the amount of inspections and tests in order to assure sufficient quality results.

CONTENT

INSPECTION PLAN FOR HULL, GRP-SANDWICH

PLAN NO. GRP 85-01

APPROVED FOR SHIP NO. ....

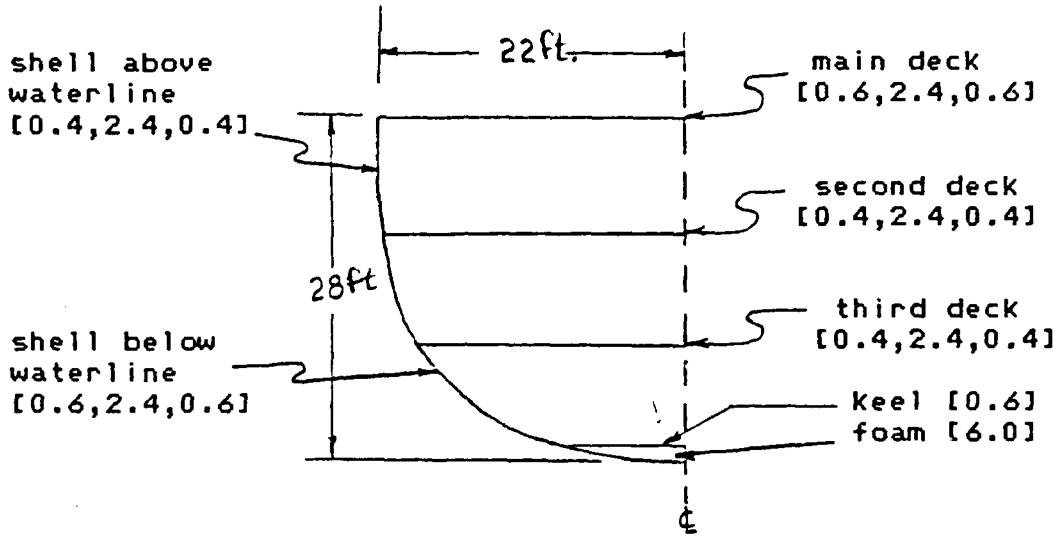
Prepared by:	1985-01-28	Lars Back	Lars Back/Qa Manager
Approved by:	1985-01-28	Lars Back	Lars Back/Qa Manager

per cubic ft.) closed cell PVC foam.

Loading: The once in 20 years estimate of the maximum bending moment is 24,616 ft-tons.

Framing: Transversely framed at 8ft intervals.

Structural Design : The midship section has a moment of inertia of 1805 ft^4. The dimensions are shown below [face/core/face in inches].



Production Method : Semi-automated, the plies are impregnator dispensed on site and then manually placed and consolidated.

Cure: Room temperature.

Material strength properties of laminate:

E_{11} = 2.6 x 10E6 psi
E_{22} = 3.0 x 10E6 psi
G = 0.45 x 10E6 psi
ν_{0° = 0.18, ν_{90° = 0.20
tensile strength = 38,000 psi
compressive Strength = 20,000 psi
ILSS = 14,000 psi
SBSS = 5,200 psi
glass content = 58%

For additional information refer to Reference [3]

APPENDIX D

RESEARCH DOCUMENTATION CONCERNING THE DEGRADATION OF UNIDIRECTIONAL GRAPHITE EPOXY LAMINATE DUE TO POROSITY OF VARIOUS TYPES AND LOCATIONS

submitted by:

RONALD D. THOMAS
&
CHRIS W. CABLE
on
12 February 1984
for
Course 3.99

TABLE OF CONTENTS

I. INTRODUCTION

The effect of void content on the performance of a high strength graphite-epoxy (GR/EP) system is dependent on the size, location and type of porosity present. It is the scope of this research to study this effect in order to eventually predict the behavior of a GR/EP system that is subject to quantifiable porosity.

This progress report describes the first phase of the research. The purpose of phase I is to intentionally introduce porosity of specific size, type and location within GR/EP unidirectional laminates and determine the degree of property degradation. The porosity was introduced by means of resin starvation, saline contamination and precure.

This report summarizes the research efforts of R.D. Thomas and C.W. Cable during the summer and fall of 1983. Experimental techniques, details of the laminate layup and cure, test results, lessons learned and recommendations are addressed.

II. Experimental Techniques

A. Resin starvation

1. Using MEK solvent, it was desired to controllably achieve an 85 +/- 10% level of resin starvation within GR/EP prepreg for further use in experimental laminates.

2. Two methods of applying MEK were used:

(a) Brushing:

Using an ordinary 1" paint brush, MEK was brushed onto GR/EP prepreg test specimens, approximately 2"X 4" in size, that were sandwiched between two pieces of porous teflon paper. Initial research [1] indicated that 90% resin starvation would be measurable by the observation of having just enough resin left to keep fibers in place during layup. 9 samples were used in two sessions. The MEK was brushed along the fibers using one downward swipe and one upward swipe for each dip. The brush side was reversed following the downward swipe.

Note: The samples were placed on a piece of aluminum honeycomb to facilitate drying. The brush was cleaned with tap water and dried between sessions. The samples were allowed to dry for at least 8 hours after brushing. See Appendix A for specific data.

Handling the samples in session one was extremely difficult. After drying, it was impossible to visually observe any difference in extent of starvation between samples, and, because of some gross fiber misalignment during handling, it

was also impossible to satisfy the criteria of "Just enough resin left to keep fibers in place". Handling was much improved during session II. This is attributable to the fact that the samples were out of the freezer for a shorter time and were less tacky as a result. It was thought that such increased exposure to MEK (20, 30, 40 dips) would certainly yield some observable resin starvation. However this was not the case, and the visual method of measuring extent of resin starvation was abandoned. Back calculation of % resin removed based on an estimated weight before treatment confirmed that the brush method itself did not meet controllability requirements. Variables such as brush absorption, pressure of swipe, lack of uniform distribution etc. led to the abandonment of the brush method.

(b). Soaking

The soaking method relied on a weight analysis to determine extent of resin starvation.

First, the percent epoxy (by weight) of the 5208/T300 GR/EP prepreg was experimentally determined to be approximately 37%. This calculation was made by soaking a sample of prepreg for an extended period, thus insuring that close to 100% epoxy was removed. The following formula was used to represent the % weight of epoxy in the prepreg:

$$\frac{\text{WEIGHT BEFORE} - \text{WEIGHT AFTER}}{\text{WEIGHT BEFORE}} = \frac{\text{WEIGHT OF EPOXY}}{\text{WEIGHT OF PREPREG}}$$

Then various extents of soaking with MEK were employed to bracket desired levels of starvation. Once bracketed, the desired levels were narrowed in on, and duplicate tests were made to gauge reproducibility. Soaking was accomplished in a 2" deep enamel bakeware tray. Standard size samples of GR/EP prepreg were sandwiched between two pieces of porous teflon paper. Soaking was performed in four sessions.

Session I

7 2"x4" samples were soaked as follows:

a). 30 min.

b). 21.5 min.

c). 10 min.

d). 15 min.

e). 2 min.

f). 5 min.

g). 7 min.

Due to improper zeroing of scale used to weigh samples a, b, c, and d, those results were invalid. Weights (before soak) were measured with the teflon paper for ease of handling. The sandwiched samples were immersed into a bath of MEK and then pulled out with the tweezers and placed on aluminum honeycomb to dry. Weights (after soaking) were measured with the paper and then the paper was weighed.

$$\frac{1.0}{0.37} * \frac{\text{Wt. w/paper before} - \text{Wt. w/paper after}}{\text{Wt. w/paper before} - \text{Wt. of paper after}} = \text{\% Resin Removed}$$

The weight of the teflon paper was found to differ only slightly between "before soak" and "after soak" conditions. For ease of handling, the weight of the paper after soaking was used.

Session II

Samples e, f, and g, were further soaked (using the same procedures as in Session I) to determine the extent of starvation at 9, 11, 13, 15, 20 and 25 minutes.
The results as shown in appendix B were fairly consistent. Some variations were due to: 1). The handling of the porous teflon paper in order to achieve weights after soak., 2). The MEK bath was not consistently renewed.
Because of its reasonable reliability, the soak method was chosen.

Session III

At this stage in the experiment it was desired to additionally achieve a 50 +/- 10% extent of resin starvation. 3 new 2"x4" samples were soaked for lengths of time varying from 30 sec. to 9 min. All three samples were soaked close to the same length of time, and then dried, weighed and further soaked. Again, the paper was weighed

after the soak. Drying times in this session were much shorter than previous sessions. Samples were only dried until they felt dry to the touch (approx. 10-15 min.). The results, shown in Appendix C show a marked sensitivity to the way the MEK bath is renewed. Fresh MEK soaks show a very consistent trend.

Session IV

Full sized pieces of GR/EP prepreg (5"x12" and 4"x12") were soaked for actual use in the experimental laminates. These pieces were carefully cut to size and thus were all approximately the same weight.

5" STD 9.3882 grams

4" STD 7.5798 grams

Using this standard and weighing the porous teflon paper before soaking reduced and therefore improved handling. Another handling improvement was achieved by placing the GR/EP pieces on the aluminum honeycomb during soaking. This caused a more uniform flow of MEK as the sample was being removed (still on the honeycomb) from the MEK bath. It also changed the drying process as it took longer now for the pieces to feel dry to the touch. The results are shown in Appendix D.

B. Saline Exposure

1. GR/EP prepreg was exposed to artificial seawater for further use in experimental laminates. A concentration of 24g. NaCl / 1000g. distilled water was used. Samples were soaked for approximately 18 hours by immersion and then dried for 8 hours.

C. Precure

1. GR/EP prepreg was precured in an oven at 350 degrees F. for 1 hour for further use in experimental laminates.

III. LAYUP

A. Scheme

1. The layup scheme is shown in Figure III-1. The crack starting strips were included for future fracture analysis.

B. Procedure

1. Standard TELAC procedures [2] were used for layup.

IV. Curing of laminate plates

A. Scheme

1. All 12"x14" plates were cured in an autoclave using the following cure cycle:

a. apply vacuum

1. 29.4 inches for plates I, II, III, V only

2. plate IV was not placed in the vacuum bag.

b. RT to 275 degrees F. (+5/-10 degrees F.) at 4-6 degrees F./min.

c. hold 1 hour

d. increase autoclave pressure to 85-100 PSIG

e. 275 degrees F. to 355 degrees F. (+/- 10 F.) at 4-6 F./min.

f. hold 2 hours

g. cool with pressure

2. Actual autoclave temperature/ pressure histogram for the cure cycle run is shown in Appendix F.

B. Procedure

1. Standard TELAC procedures [2] were used for the autoclave run with the following exceptions:

a. Placement of bleeder plies

1. Bleeder plies are normally placed on the top of the laminate using one bleeder ply for every two laminate plies. In this experiment bleeder plies were placed symmetrically; 1/2 on top and 1/2 on bottom. This was done in an attempt to balance the excess resin bleed off thus keeping induced porosity intact.

b. Sectioning of standard plate

1. To gain a large number of specimens each standard 12"x14" plate was sectioned into 3 subplates; 2-12"x5" and 1-12"x4"

using 3/4" bu 12" non porous teflon strips. These strips were intended to stop excess resin flow between subplates.

c. Post cure

1. The preliminary plies on plates 1 and 3 were badly burned during cure. Thus plate identification was questionable. Plates 1 and 3 may have been inadvertently interchanged.

V. RESULTS OF OBSERVATIONS

1. Samples were cut and prepared for observation under a microscope.

2. Significant porosity was induced.

3. The magnitude of porosity present suggests that indeed plates 1 and 3 were mismarked after cure. The porosity should have been more severe in plate 1 and was observed to be more severe in plate 3.

VI. LESSONS LEARNED

1. Handling GR/EP prepreg during pretreatment was a difficult task. The following techniques improve handling:

a. Handle less (see session 4 of section 2)!

b. Renew the MEK bath for each soak.

c. Keep ER/EP out of freezer for short periods only, and return them to freezer after pretreatment before layup.

d. Use porous teflon to sandwich the GR/EP.

2. Layup of resin starved plies was a challenge.

a. The tackiness that impedes you during pretreatment helps you in some aspects of layup.

b. Practice layup using starved plies ahead of time.

3. Working with the 16 Dept. technicians in charge of their autoclave was a professional pleasure. Future liaison should be initiates through Prof. Lagace x3628 and Dave Brewer x2430.

4. 3 Dept should have its own large capacity freezer and layup tables. Travelling back and forth between 16 Dept freezer and 3 Dept pretreatment labs was cumbersome.

5. Pay close attention to identification markings. Peel plies will burn!

6. Keep prepreg tightly sealed in freezer to prevent condensation.

7. The method used to separate the standard plate into three sections was successful and is an effective way to increase the variety of pretreatments used. This was done for economic reasons. The cost of the autoclave run was high, and it was desired to get a lot out of one run.

8. When sandwiching the GR/EP between porous teflon paper, put one piece of paper on the GR/EP then peel the GR/EP prepreg backing paper off before putting second piece of teflon paper on.

9. Wear rubber gloves for all handling of GR/EP.

VII. TESTING

A. GENERAL PROCEDURE

The three point bending test as per ASTM was performed to assess the effects of the induced voids/porosity. Test specimens were cut using a diamond tip saw from the four previously layed up and cured plates. ASTM Specimen geometry requirements and the scheme for cutting specimens are shown in Appendix H. This sampling scheme allowed the effects of voids/porosity distribution as a function of plate location to be assessed.

B. RESULTS

The load at specimen failure was initially used to calculate the interlaminar shear strength, S. This load corresponded to a drastic change of the slope of the applied load versus specimen deflection strip chart output. We classified this approach as the final failure criteria. Appendix H provides a tabular summary of test results performed on selected specimens. The test results are inconsistent. For example, the control specimen (plate 2-3) had an average shear strength lower than all three sub-plates cured out of the vacuum bag. This inconsistency is thought to be due to not using an initial degradation load to determine S.

In an attempt to evaluate the "true" shear strength, the load at the "first significant reduction in modulus" was used. Appendix G provides a tabular summary of test results on selected specimens. These results appear to be more

AD-A158 967 QUALITY ASSESSMENT OF GLASS REINFORCED PLASTIC SHIP HULLS IN NAVAL APPLIC..(U) MASSACHUSETTS INST OF TECH CAMBRIDGE DEPT OF OCEAN ENGINEERIN.. R D THOMAS ET AL. 3/3

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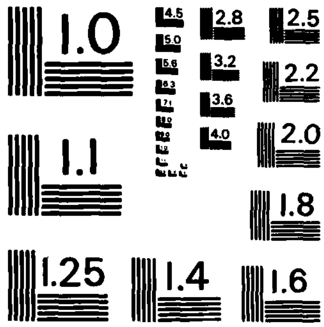

1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6

consistent, in that plate 4 is clearly weaker as expected, but not conclusive. For example, the rather severe resin starvation pretreatment applied to sub-plate 1-3 led to only a 7.8% difference in strength as compared to the control sample 2-3. This difference is less than the 8.3% strength standard deviation found in the control sample.

C. DISCUSSION

At first nothing about the results "hit us between the eyeballs"! In order to determine any "hidden" trends further statistical analysis was performed. Specifically, mean values and standard deviations were obtained and summarized in Appendix H. The average strength of plate 4 was found to be the lowest as expected. However, within all plates different pretreatments did not result in any significant differences in strength as measured by the short beam shear test used.

Appendices J and K show the effects of void/porosity distribution. Based on the first degradation criteria, only plate 4 shows a dependence of strength on the location of the specimen. Based on the final failure criteria, plate 2 shows centrally located specimens to be significantly stronger.

Appendix L shows a comparative arrangement of stress-strain curves for several sub-plates. These curves are the inverse tracings of strip chart load versus time graphs. The data

does not show any significant distinction between control and void induced samples.

Appendix M shows micrographs of each of the subplates. It is evident that the pretreatments used were successful in that voids/porosity were introduced. Plate 4 shows particularly significant porosity.

The differences in strength (see Appendix H) suggest that indeed plates 1 and 3 were mismarked after cure. The strength should have been lower in plate 1 and was observed to be lower in the plate marked 3.

VIII. RECOMMENDATIONS FOR FUTURE EFFORTS

It is apparent that the short beam shear test is not the appropriate test to identify the effects of voids/porosity. The following course of action is proposed:

1. Conduct fatigue tests on specimens from the same pre-treated plates.

2. Further identify the location/extent of voids/porosity using available techniques and correlate to distribution effects found in plate 4.

IX. REFERENCES

1."Development of Acceptance Criteria for Graphite/Epoxy Structures"; Naval Air Systems Command Final Report, 1982

2. Paul A. Lagace and John C. Brewer, Technology Laboratory for Advanced Composites (TELAC) Manufacturing Course Notes: 1982

APPENDIX A

RESIN STARVATION DATA OBTAINED BY THE BRUSHING METHOD

SAMPLE #	# OF SWIPES	WEIGHT(gm) AFTER	% RESIN REMOVED
* 1	1	1.282	0.00
* 2	2	1.066	40.20
* 3	3	1.211	8.34
* 4	5	1.096	33.60
* 5	7	1.075	38.20
* 6	9	1.086	35.80
** 7	20	0.905	75.69
** 8	30	0.975	60.10
** 9	40	1.043	45.20

*- DENOTES SESSION I
**- DENOTES SESSION II

ASSUMED 2" BY 4" STD. SAMPLE OF 1.249 GRAMS & 36.44% EPOXY BY WEIGHT

CONCLUSION: RESULTS ERRATIC, BRUSH METHOD QUESTIONABLE

APPENDIX B

RESIN STARVATION DATA OBTAINED BY SOAK METHOD, SESSIONS I & II

SAMPLE	SOAK TIME (min)	WT BEFORE	WT AFTER	% RESIN REMOVED
* e	2	1.191	0.814	85.6
* f	5	1.282	0.886	83.4
* g	7	1.275	0.874	85.6
** g′	9	1.275	0.821	96.2
** f′	11	1.282	0.829	95.1
** e′	13	1.191	0.756	98.6
** e"	15	1.191	0.754	99.2
** f"	20	1.282	0.815	98.3
** g"	25	1.275	0.810	98.5

*- DENOTES SESSION I
**- DENOTES SESSION II

ASSUMPTION: BASED ON 37 % RESIN BY WEIGHT OF ORIGINAL 2" BY 4" SAMPLE
NOTE: SAMPLES a,b,c & d WERE INVALID DUE TO MEASURING ERROR.

APPENDIX C

RESIN STARVATION DATA OBTAINED BY SOAK METHOD, SESSION III

SAMPLE	SOAK TIME (sec)	% RESIN REMOVED
A-1	30	50.7 *
B-1	33	39.1 *
C-1	40	75.9 *
A-2	65	79.2
B-2	65	84.7
C-2	65	83.5
A-3	95	83.4
B-3	98	93.6
C-3	105	91.5
A-4	125	97.9
B-4	128	98.6
C-4	135	93.0
A-5	185	68.5 *
B-5	188	73.7 *
C-5	195	78.0 *
A-6	245	76.6
B-6	248	84.1
C-6	255	81.8
A-7	305	88.5
B-7	308	92.7
C-7	315	95.4
A-8	365	94.1
B-8	368	92.9
C-8	375	95.2
A-9	395	83.7 *
B-9	398	83.1 *
C-9	405	79.6 *
A-10	425	99.6
B-10	428	98.2
C-10	435	98.5
A-11	455	95.9
B-11	458	93.7
C-11	465	97.6
A-12	485	102.0
B-12	488	97.9
C-12	495	98.6
A-13	515	85.2 *
B-13	518	88.4 *
C-13	528	92.6 *
A-14	545	94.6
B-14	548	90.8
C-14	555	89.1

* -- DENOTES NEW OR RENEWED MEK BATH FOR 2" BY 4" SAMPLES

NOTE: RESULTS USING NEW OR RENEWED MEK BATH WERE CONSISTENT. THESE SOAK TIMES WERE THEN USED AS GUIDELINES FOR THE PREPARATION OF THE LAYUP SPECIMENS.

APPENDIX D

RESIN STARVATION DATA OBTAINED BY SOAK METHOD (used for layup)

SAMPLE #	SIZE (in)	TREATMENT * (% ,sec)	WT OF TEFLON BEFORE SOAK (gm)	WT OF TEFLON BEFORE SOAK (gm)	% EPOXY REMOVED
AA	5	50 & 30	2.81	9.96	64.5
BB	5	85 & 360	2.64	8.86	91.6
CC	5	85 & 330	2.97	8.96	98.0
DD	5	50 & 25	3.04	9.71	78.1
EE	5	85 & 300	3.25	8.90	96.0
FF	5	85 & 300	3.08	9.26	92.4
GG	5	85 & 240	2.70	10.39	49.0
HH	5	85 & 240	2.55	10.13	51.9
II	4	50 & 240	2.63	8.10	75.2
JJ	4	50 & 155	2.23	8.61	43.1
KK	4	50 & 155	2.61	8.34	65.9
LL	5	50 & 20	2.81	9.81	68.6
MM	5	50 & 20	2.85	10.00	76.0
NN	4	85 & 270	2.61	8.29	67.7
OO	4	85 & 240	2.66	7.53	96.7
PP	4	85 & 270	2.38	7.99	70.0
RR	4	50 & 20	2.92	8.33	77.4
SS	5	85 & 240	2.65	7.97	80.4
TT	5	50 & 20	2.67	10.20	53.6
UU	5	85 & 240	2.67	9.16	83.5

NOTE: ASSUMED STANDARD WEIGHT OF 5" BY 12" SAMPLE EQUAL TO 9.39 gms
ASSUMED STANDARD WEIGHT OF 4" BY 12" SAMPLE EQUAL TO 7.58 gms

*- TREATMENT INDICATES THE % EPOXY STARVATION DESIRED AND SOAK TIME OF THE SAMPLE.

APPENDIX E

GRAPHITE EPOXY PLATE LAYUP SCHEME

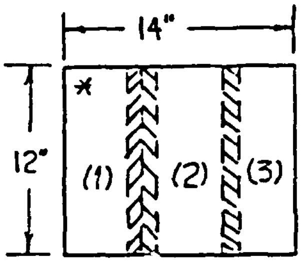


Plate I - 12 ply 5208/T300

plate I-(1) - ply 6 resin starved 92.%
plate I-(2) - plies 6 & 7 resin starved 97.0%
plate I-(3) - plies 6,7,& 8 resin starved 84.8%

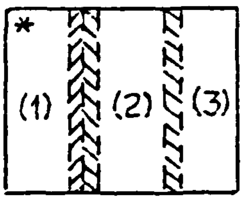


Plate II - 12 ply 5208/T300
plate II-(1) - plies 6 & 7 precured
plate II-(2) - plies 6 & 7 saline soaked
plate II-(3) - control

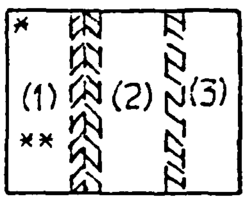


Plate III - 12 ply 5208/T300

plate III-(1) - ply 6 resin starved 53.6%
plate III-(2) - plies 6 & 7 resin starved 50.5%
plate III-(3) - plies 6,7 & 8 resin starved 58.9%

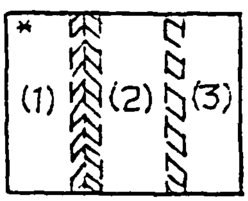


Plate IV - 12 ply 5208/T300
out of vacuum bag

plate IV-(1) - plies 6 & 7 saline soaked
plate IV-(2) - plies 6 & 7 resin starved 80.6%
plate IV-(3) - control

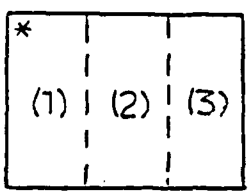


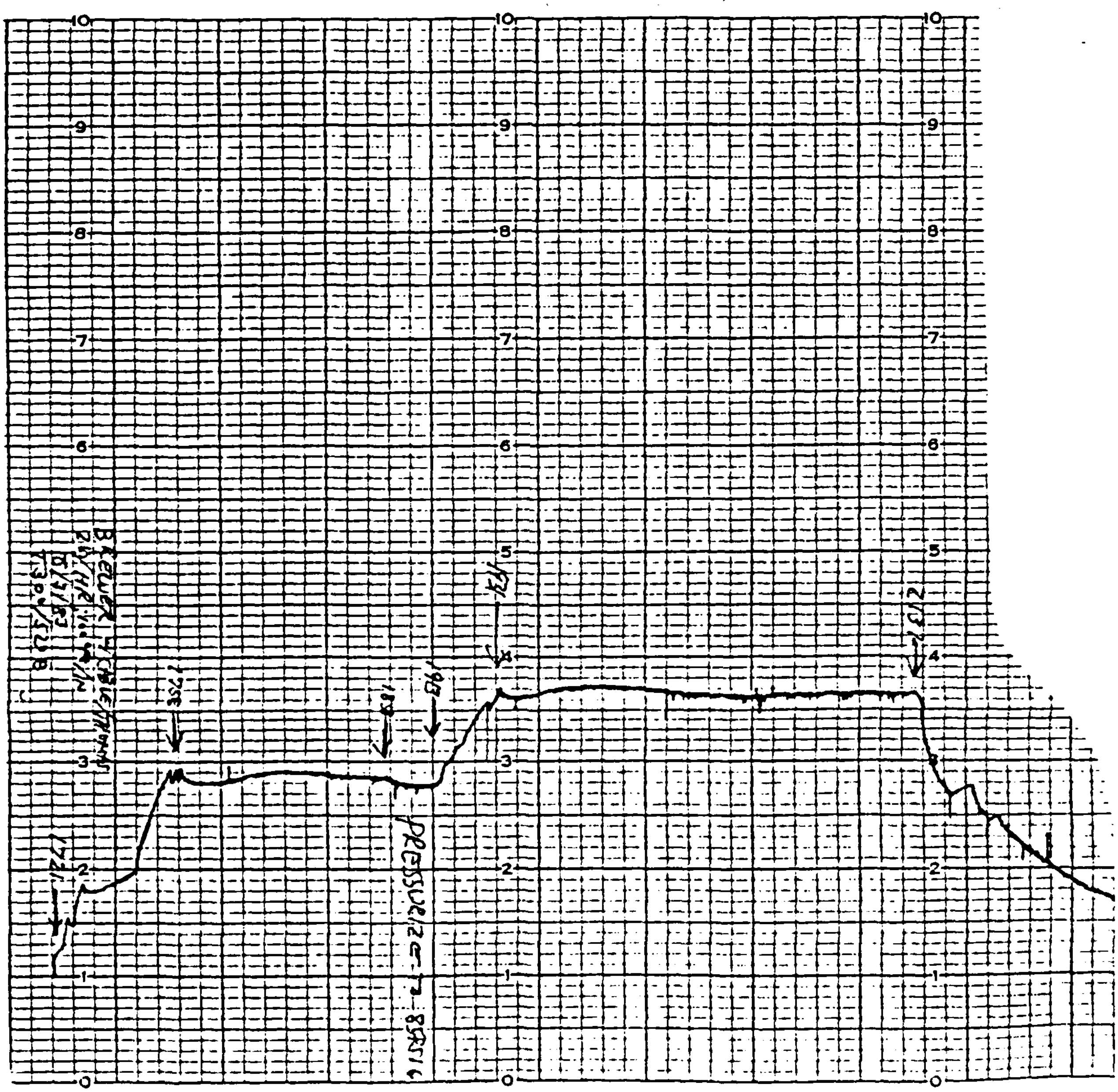
Plate V - 8 ply 5208/T300 Control Sample

* annotates top of plies
** 3/4"x 12" nonporous teflon strips placed between plies 6 & 7 as crack starters

NOTE:
Extent of resin starvation reported is an average of the starved plies

APPENDIX F

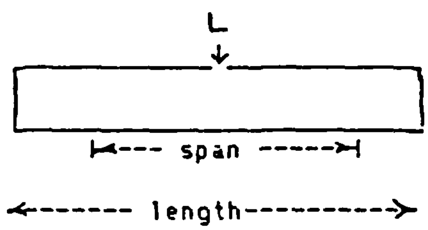
LAMINATE AUTOCLAVE CURE DATA



APPENDIX G-1

TEST SPECIMEN GEOMETRY REQUIREMENTS AND CUTTING SCHEME

G-1 ASTM SPECIMEN GEOMETRY REQUIREMENTS



span = 5 times thickness

length = 7 times thickness

NOTE: A SPAN OF 0.33 INCHES WAS USED FOR ALL SPECIMENS FROM PLATE 1, 2 AND 3.
A SPAN OF 0.39 INCHES WAS USED FOR ALL SPECIMENS FROM PLATE 4.
ACTUAL THICKNESS VARIED SLIGHTLY, BUT THE SPAN WAS KEPT THE SAME AS NOTED ABOVE. SINCE SHEAR STRENGTH EQUALS:

$$S = \frac{0.75\,P}{b*d}$$

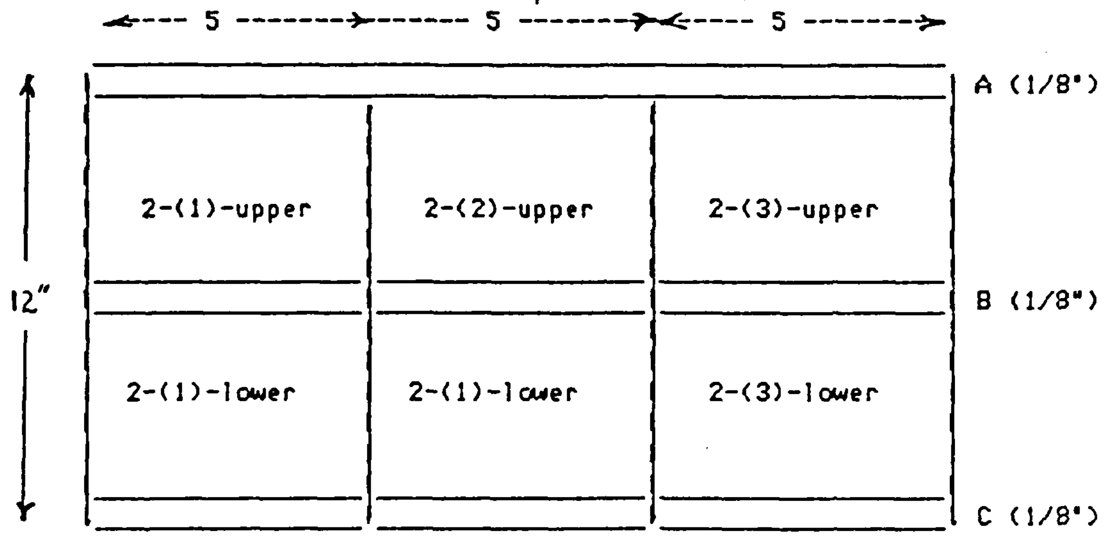
WHERE: S= SHEAR STRENGTH
P= FAILURE LOAD
d= SPECIMEN THICKNESS
b= SPECIMEN WIDTH = 0.125 INCHES

THE THICKNESS VARIATION WAS NOT CONSIDERED SIGNIFICANT.

APPENDIX G-2

SCHEME FOR CUTTING SAMPLES

Example: Plate #2



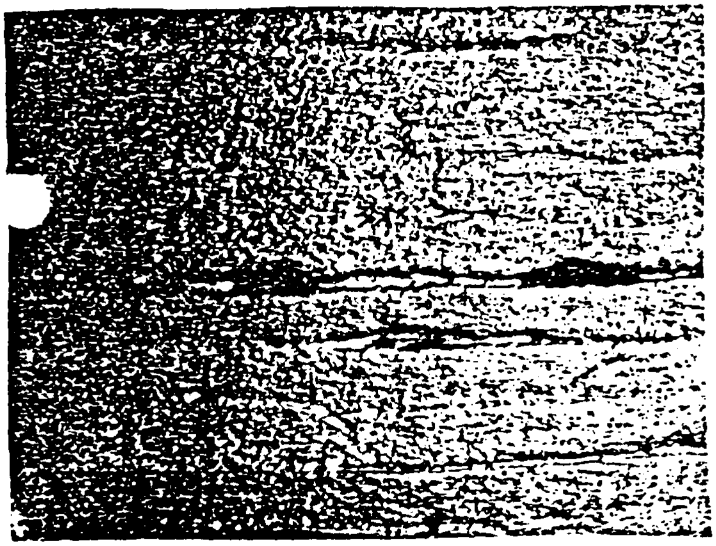
Each strip (A,B, and C) was cut into 1/2" lengths i.e. 2-3-A-1, 2-3-A-2, etc.

NOTE; in plate #4, 3/4" lengths were used to accomodate the increased thickness

APPENDIX H

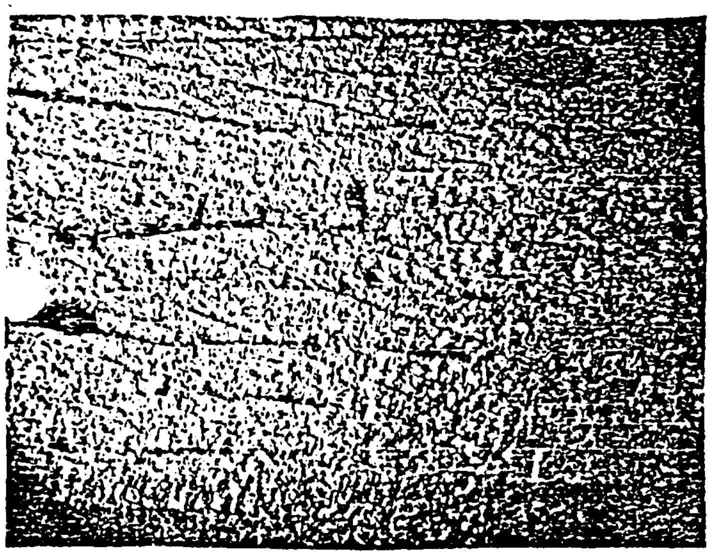
SHEAR STRENGTH OF SELECTED "VOID INDUCED" SPECIMENS

PLATE #	TREATMENT	SPECIMEN	* FINAL FAILURE (KSI)	** INITIAL DEGRADATION (KSI)		MEAN (KSI)	STANDARD DEVIATION (KSI)
		1-1-A-4	13.18	7.73			
		1-1-A-5	13.47	6.47			
		1-1-A-6	14.14	8.92			
1-1	PLY 6; 92.4%	1-1-C-4	11.92	8.87			
	RESIN STARVED	1-1-C-5	9.62	8.72	*	12.41	1.47
		1-1-C-6	10.65	8.91	**	8.83	0.98
		1-1-E-1	11.67	9.82			
		1-1-E-3	11.78	9.78			
		1-1-E-4	14.40	9.55			
		1-1-E-5	13.31	9.48			
		1-2-A-4	15.46	10.05			
		1-2-A-5	14.38	9.74			
		1-2-A-6	12.79	9.95			
1-2	PLIES 6&7; 97%	1-2-C-4	12.98	9.38			
	RESIN STARVED	1-2-C-5	13.08	8.30	*	13.88	1.22
		1-2-C-6	15.93	9.31	**	9.61	0.53
		1-2-E-3	12.00	9.76			
		1-2-E-4	13.96	10.13			
		1-2-E-5	14.33	9.89			
		1-3-A-3	11.89	9.63			
		1-3-A-4	12.44	10.13			
		1-3-A-5	10.91	9.76			
1-3	PLIES 6,7&8	1-3-C-3	12.00	9.01			
	84.8%	1-3-C-4	12.68	9.31	*	13.10	2.15
	RESIN STARVED	1-3-C-5	13.85	9.20	**	9.50	0.55
		1-3-E-1	9.44	8.36			
		1-3-E-3	15.56	9.76			
		1-3-E-4	16.33	10.39			
		1-3-E-5	15.85	9.40			



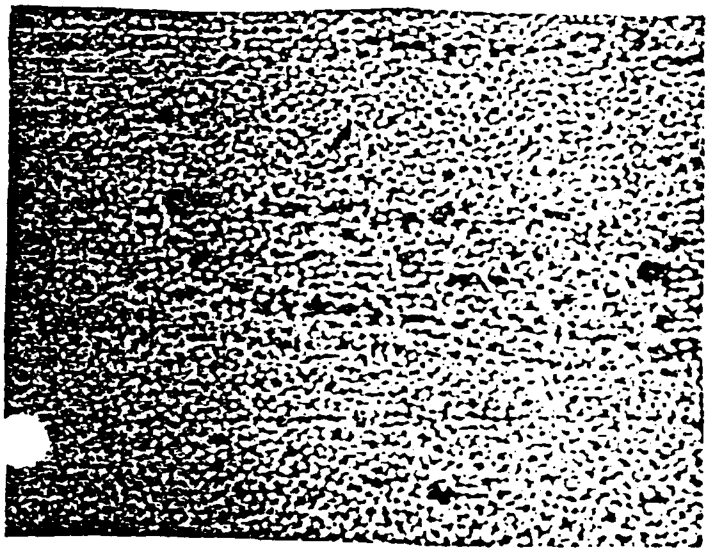
SUB-PLATE 4-1 (51X)

VOIDS NEAR SURFACES AS WELL AS IN CENTRAL LAYERS

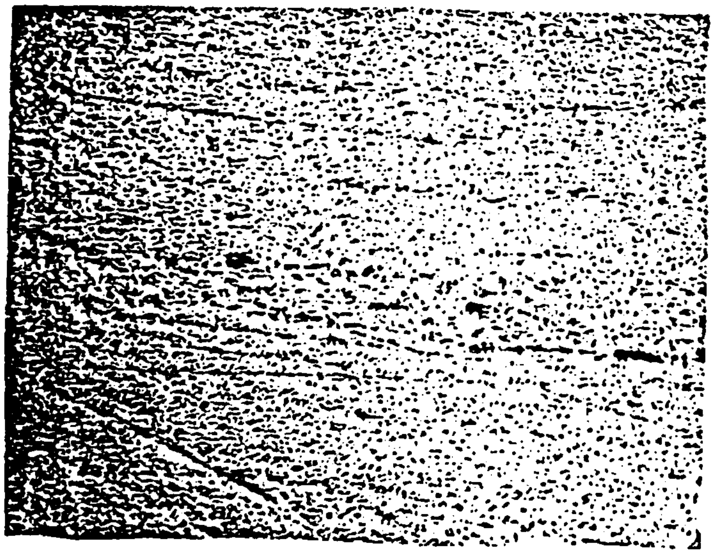


SUB-PLATE 4-2 (51X)

PLATE 4

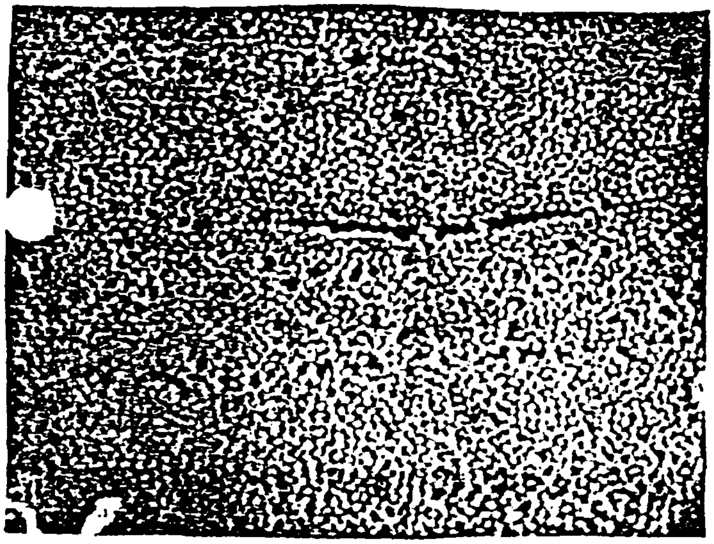


SUB-PLATE 3-3 (200X)

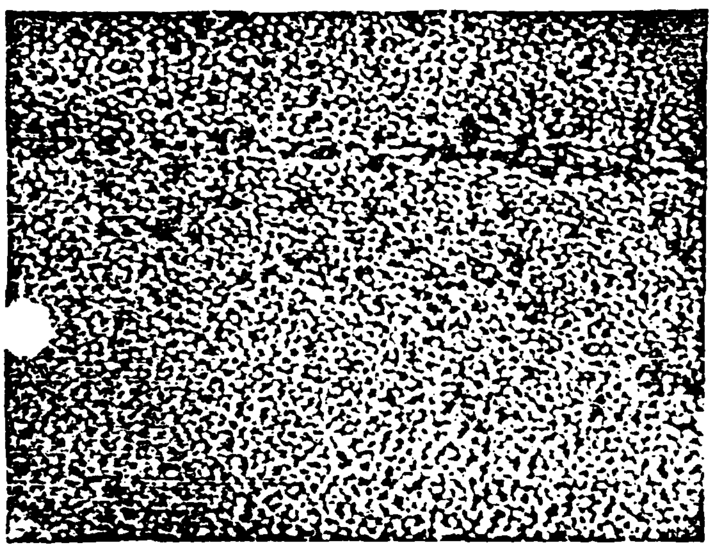


SUB-PLATE 3-3 (102X)

PLATE 3 (CONT.)

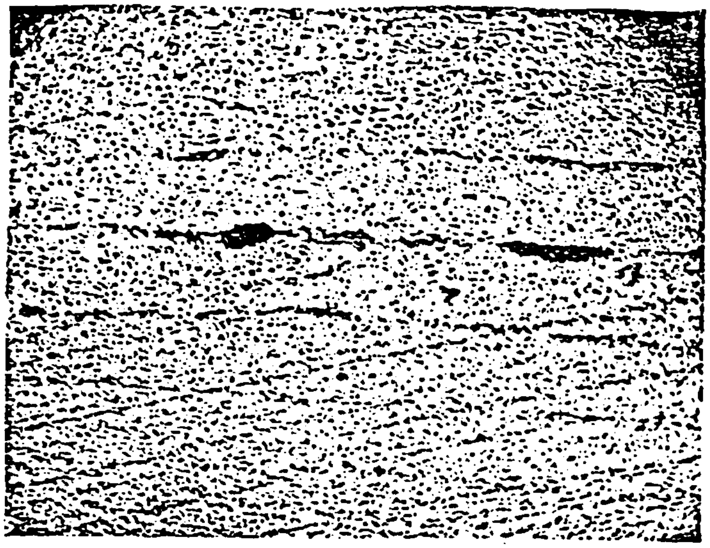


SUB-PLATE 3-1 (200X)

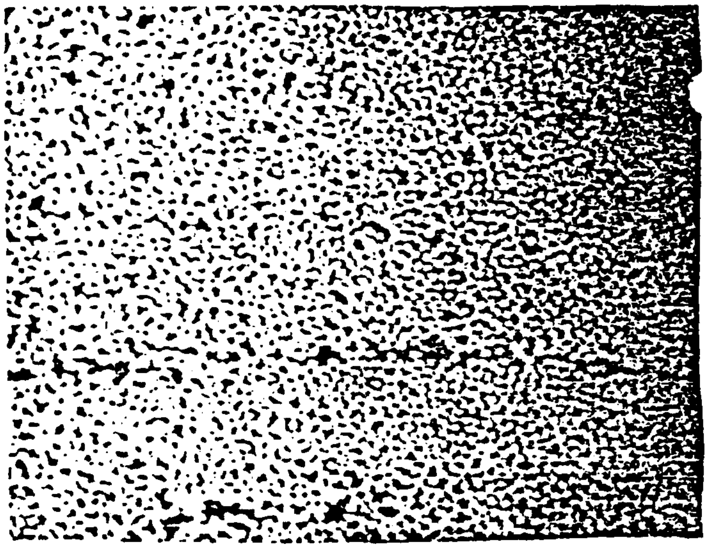


SUB-PLATE 3-2 (200X)

PLATE 3

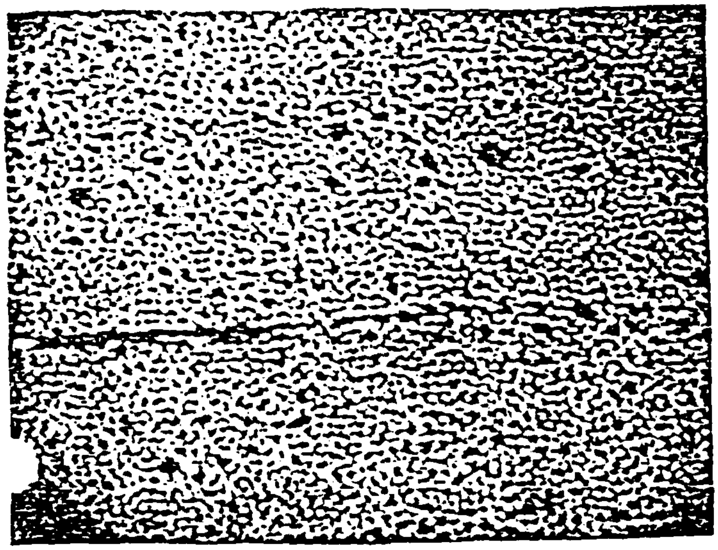


SUB-PLATE 2-2 (102X)



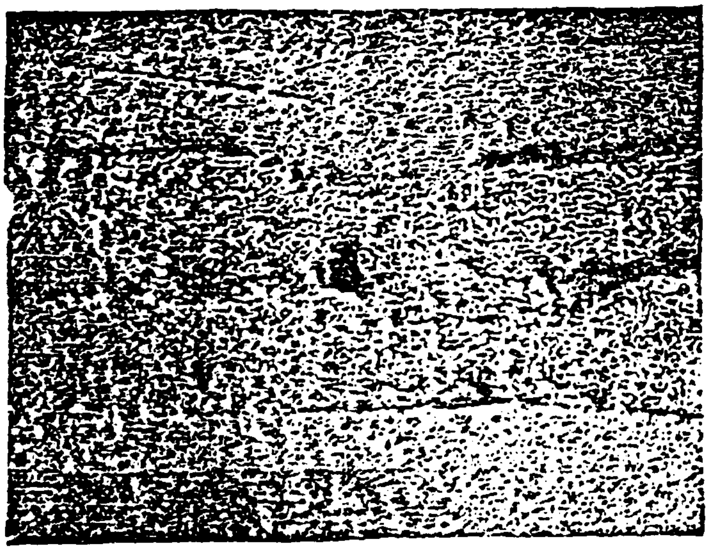
SUB-PLATE 2-3 (200X)

PLATE 2 (CONT.)



SUB-PLATE 1-3 (200X)

PLATE 1 (CONT.)

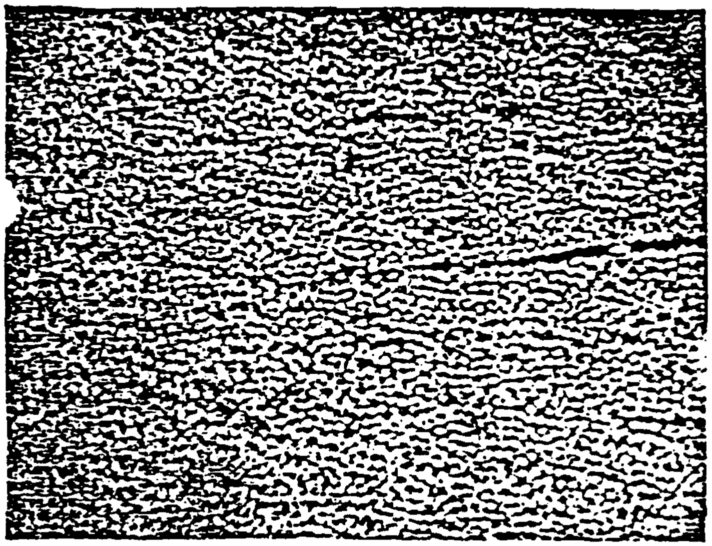


SUB-PLATE 2-1 (102X)

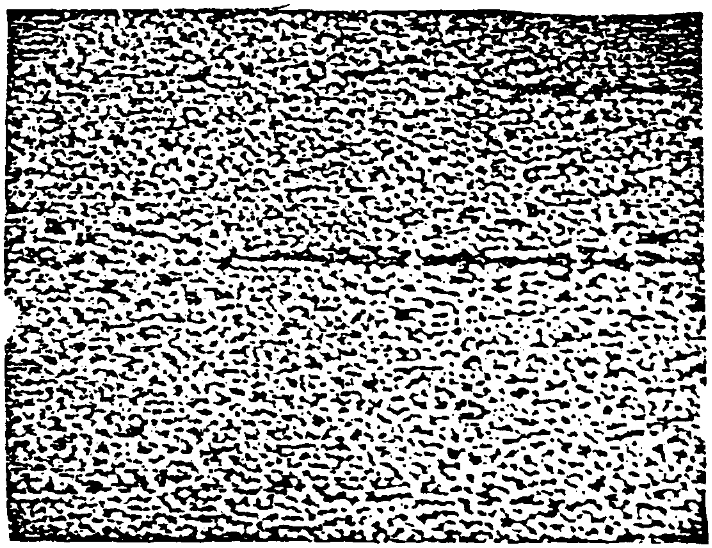
PLATE 2

APPENDIX M

MICROGRAPHS OF SELECTED SPECIMENS



SUB-PLATE 1-1 (200X)



SUB-PLATE 1-2 (200X)

PLATE 1

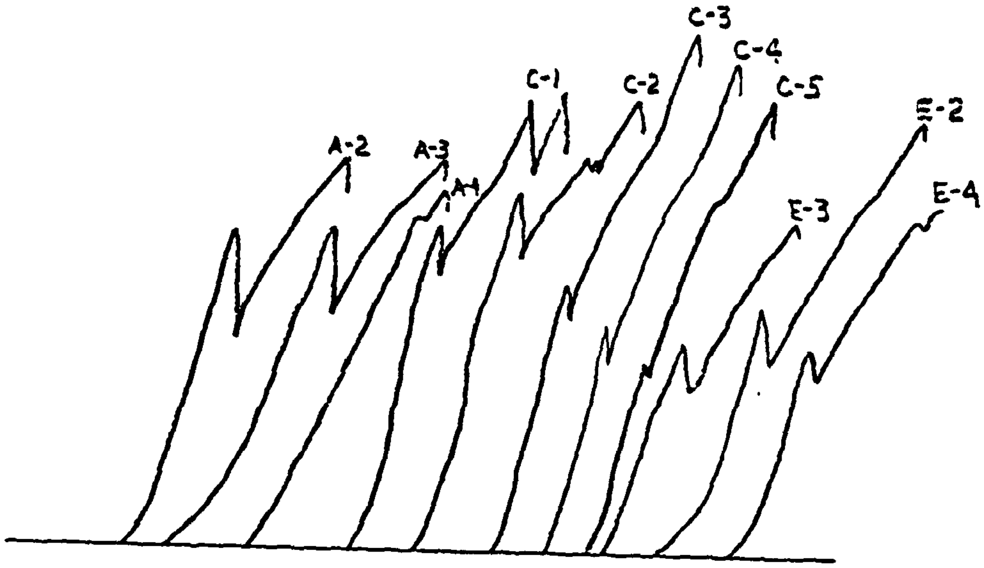


PLATE 3-3

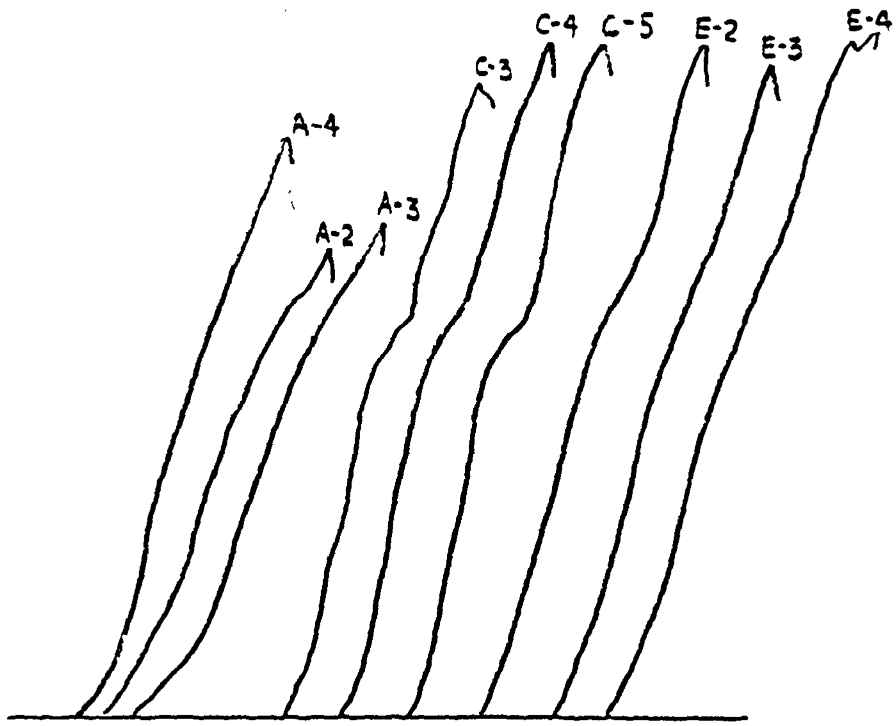


PLATE 4-3

APPENDIX L

STRESS-STRAIN-MODULUS TREND ANALYSIS (TRACINGS)

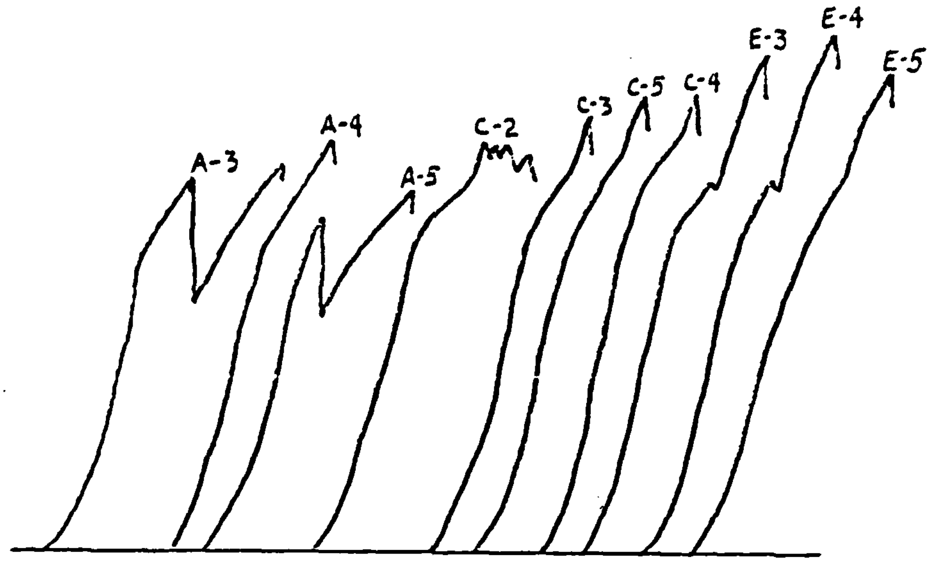


PLATE 1-3

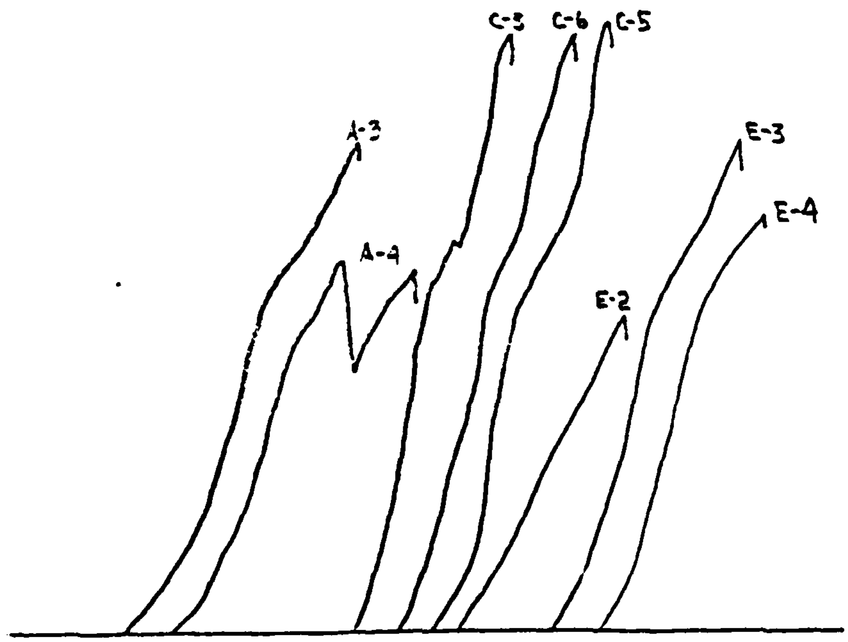


PLATE 2-3

APPENDIX K

EFFECT OF VOID/POROSITY DISTRIBUTION BASED ON FINAL FAILURE CRITERIA

PLATE #	PLATE LOCATION	MEAN (KSI)	STANDARD DEVIATION
2-1	A	13.95	0.085
2-1	C	15.64	0.285
2-1	E	12.63	0.903
2-2	A	12.08	0.786
2-2	C	14.87	0.614
2-2	E	11.28	1.455
2-3	A	12.38	1.503
2-3	C	15.88	0.408
2-3	E	11.44	2.020

NOTE: PLATE 2 RESULTS BASED ON FINAL FAILURE CRITERIA WERE FELT TO BE REPRESENTATIVE. THE ABOVE DATA REFLECTS A TREND OF HIGHER STRENGTH IN CENTRALLY LOCATED SPECIMENS, LOCATION C.

APPENDIX J

EFFECT OF VOID/POROSITY DISTRIBUTION BASED ON INITIAL DEGRADATION

PLATE #	PLATE LOCATION A		C		E	
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
1-1	7.71	1.00	8.83	0.82	9.66	0.15
1-2	9.91	0.13	8.99	0.49	9.93	0.15
1-3	9.84	0.21	9.17	0.12	9.48	0.74
2-1	9.13	0.34	8.56	0.29	8.46	0.80
2-2	9.15	0.14	8.54	0.72	8.67	0.83
2-3	9.38	0.19	8.32	0.75	8.60	0.63
3-1	9.67	0.58	8.26	0.51	7.13	1.46
3-2	8.71	0.46	8.09	0.18	8.85	0.20
3-3	9.17	0.41	8.40	0.04	8.72	0.15
4-1	5.94	0.17	7.53	0.48	5.70	0.13
4-2	6.90	0.12	7.28	0.05	5.80	0.13
4-3	5.63	0.16	7.36	0.08	5.41	0.35

NOTE: THE DATA REFLECTS A WEAK TREND TOWARD LOWER STRENGTH IN CENTRALLY LOCATED SPECIMENS FROM PLATES 1,2 & 3 BUT A DEFINITE INCREASE IN STRENGTH FOR CENTRALLY LOCATED SPECIMENS FROM PLATE 4.

APPENDIX I

GRAPHICAL REPRESENTATION OF FINAL & INITIAL FAILURE STRESS

Example: Strip chart for specimen 1-2-A-6
Showing difference between final
failure and initial degradation

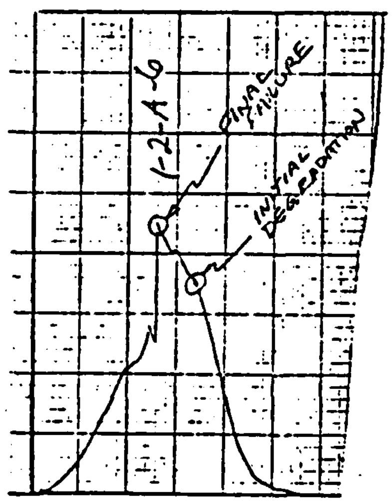


PLATE 4

	4-1-A-2	12.70	6.06			
	4-1-A-3	11.15	5.69			
	4-1-A-4	12.78	6.06			
4-1 PLIES 6&7	4-1-C-3	14.20	7.31			
SALINE SOAKED	4-1-C-4	14.10	7.09	*	13.50	1.05
(OUT OF VACUUM BAG)	4-1-C-5	14.70	8.20	**	6.39	0.87
	4-1-E-2	14.05	5.55			
	4-1-E-3	14.34	5.87			
	4-1-E-4	13.45	5.69			
	4-2-A-2	12.00	6.92			
	4-2-A-3	12.27	7.04			
	4-2-A-4	14.24	6.74			
4-2 PLIES 6&7	4-2-C-3	13.08	7.21	*	13.39	0.87
80.8%	4-2-C-4	14.34	7.34	**	6.77	0.60
RESIN STARVED	4-2-C-5	14.40	7.30			
(OUT OF VACUUM BAG)	4-2-E-3	13.10	5.67			
	4-2-E-4	13.70	5.92			
	4-3-A-2	12.56	5.51			
	4-3-A-3	14.07	5.86			
	4-3-A-4	13.62	5.52			
4-3 CONTROL	4-3-C-2	14.08	7.39	*	13.58	1.74
SAMPLE	4-3-C-3	15.48	7.45	**	6.14	0.91
(OUT OF VACUUM BAG)	4-2-C-4	14.80	7.25			
	4-3-E-1	9.14	4.95			
	4-3-E-2	14.49	5.49			
	4-3-E-3	13.95	5.80			

ALL SPECIMENS ARE 1/2"X1/8"X.062" THICK
EXCEPT PLATE 4 SPECIMENS WHICH ARE 3/4"X
1/8"XVARYING THICKNESS OF APPROXIMATELY .08".

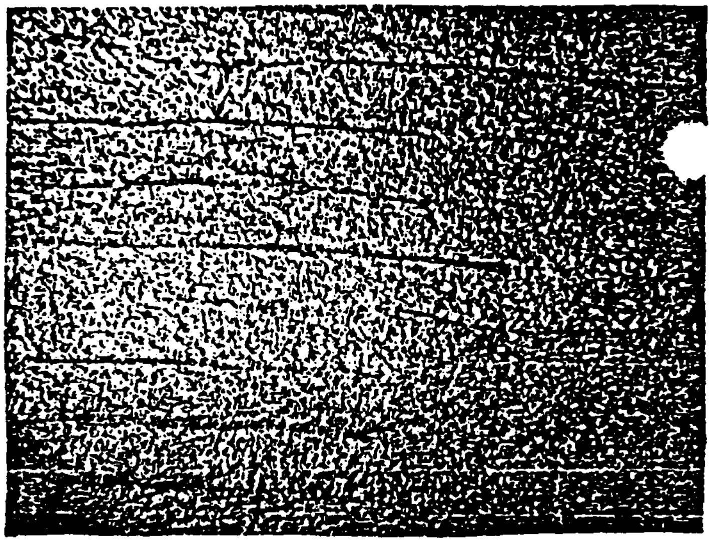
NOTES (1) : PLATE 4 WAS LOCATED OUT OF THE VACUUM BAG.
(2) : PLATES 1&3 MAY HAVE BEEN INADVERTENTLY SWITCHED DUE TO POSSIBLE LABELING ERROR.
(3) : INITIAL DAMAGE STRESS WAS DETERMINED AT THE POINT ON THE APPLIED STRESS-CONSTANT STRAIN RATE STRIP CHART RECORDING WHERE THE FIRST OBSERVABLE MODULUS (SLOPE) CHANGE WAS EVIDENT. (see Appendix I for graphical explanation)

PLATE 3

	3-1-A-4	11.32	10.19			
	3-1-A-5	12.71	9.96			
	3-1-A-6	10.73	8.87			
3-1 PLY 6 RESIN	3-1-C-4	14.71	8.84			
STARVED 53.6%	3-1-C-5	13.81	8.33	*	12.65	1.23
	3-1-C-6	13.80	7.61	**	8.75	0.93
	3-1-E-3	12.11	7.37			
	3-1-E-4	12.93	8.79			
	3-1-E-5	11.70	5.23			
	3-2-A-4	10.92	9.13			
	3-2-A-5	8.88	8.88			
	3-2-A-6	8.08	8.08			
3-2 PLIES 6&7	3-2-C-4	10.70	8.28			
50.5%	3-2-C-5	11.43	7.86	*	10.70	1.32
RESIN STARVED	3-2-C-6	11.17	8.14	**	8.55	0.45
	3-2-E-3	10.71	8.57			
	3-2-E-4	12.42	9.03			
	3-2-E-5	12.00	8.94			
	3-3-A-2	12.00	9.17			
	3-3-A-3	12.22	9.22			
	3-3-A-4	11.00	9.12			
3-3 PLIES 6,7&8	3-3-C-3	13.60	8.35			
58.9% RESIN	3-3-C-4	12.96	8.45	*	11.87	1.09
STARVED	3-3-C-5	11.98	8.39	**	8.76	0.33
	3-3-E-2	12.54	8.54			
	3-3-E-3	10.22	8.70			
	3-3-E-4	10.29	8.91			

PLATE 2

		2-1-A-4	13.86	8.79			
		2-1-A-6	14.03	9.47			
2-1	PLIES 6&7	2-1-C-4	15.73	8.60			
	PRECURED @	2-1-C-5	15.25	8.90	*	14.09	1.43
	350 F-1 HR	2-1-C-6	15.93	8.19	**	8.87	0.61
		2-1-E-3	13.90	9.00			
		2-1-E-4	12.08	9.05			
		2-1-E-5	11.90	7.34			
		2-2-A-3	12.54	9.26			
		2-2-A-4	10.97	8.95			
		2-2-A-5	12.72	9.24			
2-2	PLIES 6&7	2-2-C-2	14.61	7.52			
	SALINE SOAKED	2-2-C-5	15.48	9.07	*	12.92	1.81
		2-2-C-6	14.03	9.03	**	8.79	0.69
		2-2-E-4	9.82	7.69			
		2-2-E-5	9.82	8.60			
		2-2-E-6	12.73	9.73			
		2-3-A-3	14.25	9.63			
		2-3-A-4	10.57	9.19			
		2-3-A-5	12.30	9.32			
2-3	CONTROL	2-3-C-3	15.67	8.63			
	SAMPLE	2-3-C-4	15.52	7.28	*	13.23	2.41
		2-3-C-5	16.45	9.00	**	8.76	0.73
		2-3-E-2	8.70	7.76			
		2-3-E-3	13.50	8.77			
		2-3-E-4	12.11	9.27			



SUB-PLATE 4-3 (51X)

PLATE 4 (CONT.)

APPENDIX N

ADMINISTRATIVE SUMMARY

16 Dept. autoclave technician...John Brewer...x-2430 office

x-3553 layup room

x-7503 autoclave room

3 Dept. testing technician...Dave Moavenzaden.......x-2412

16 Dept. autoclave administrator.Paul Lagace........x-3628

1/2/3 Dept. machine shop technician..Art Rudolph....x-2720

MIT account number used...........................93309

APPENDIX E-1

EQUIVALENT CRACK LENGTH MODEL FOR ANALYSIS OF THE EFFECT OF VOIDS [37]

$$K_{II_c} = C_1 \tau \sqrt{a} \approx C_2 \tau \sqrt[6]{V_v}$$

K_{II_c} = Critical Stress Intensity Factor Mode II

τ = Interlaminar Shear Strength

a = Crack Length

V_v = Void Content

APPENDIX E-2

ADAPTED MODEL USED TO PREDICT THE REDUCTION IN COMPRESSIVE STRENGTH DUE TO VOIDS

A macroscopic model by Foye [37] assumes:

1. the fiber content is the same in a void area as it is in an unvoided area
2. the reinforcement in the void is totally ineffective for resisting longitudinal-transverse shear.

Equation (V-1) is adapted from that model, and is used to predict the trend of comoressive strength reduction in GRP.

$$\sigma_c = \sigma_o \left\{ \frac{1 - 4.88 V_v + 5.95 V_v^2}{1 + 2.44 V_v} \right\} \qquad [V\text{-}1]$$

σ_c = COMPRESSIVE STRENGTH WITH VOIDS

σ_o = COMPRESSIVE STRENGTH W/O VOIDS

V_v = VOID CONTENT

APPENDIX F-1

DEVELOPMENT OF SHEAR PROPAGATION OF DELAMINATIONS MODEL [40]

$$\frac{P_{CR}}{\sqrt{\gamma_a}} = 2\sqrt{\frac{b}{\phi_3}}$$

P_{CR} = MAGNITUDE OF CRITICAL LOAD AT WHICH PROPAGATION OF DELAMINATION IS IMMINENT

γ_a = SPECIFIC ADHESIVE SURFACE FRACTURE ENERGY

b = WIDTH

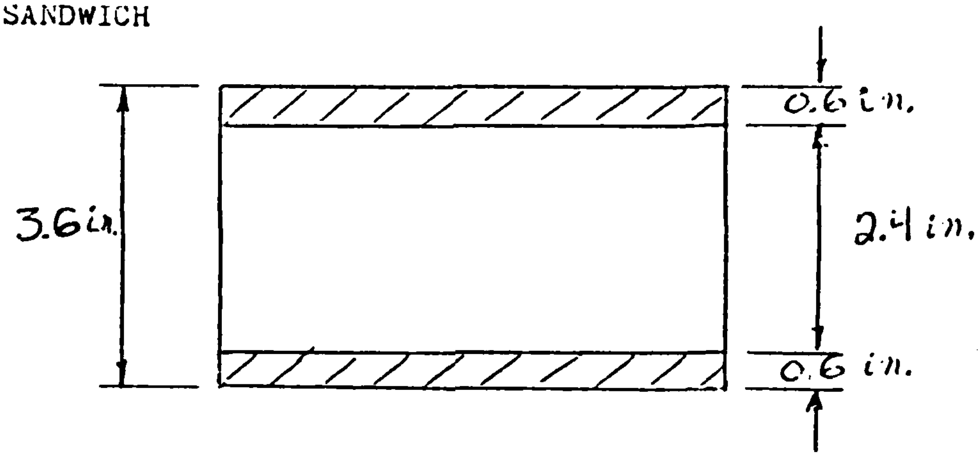
ϕ_3 = A FUNCTION OF

- FLAW LOCATION
- MODULUS
- MOMENT OF INERTIA
- SIZE OF BEAM
- SIZE OF FLAW

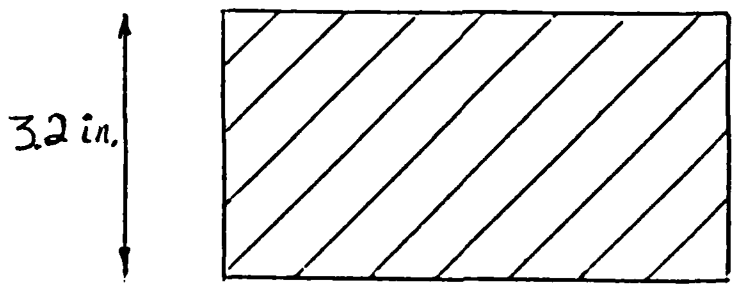
APPENDIX F-2

CALCULATION OF DIMENSIONS FOR EQUIVALENT FLEXURAL RIGIDITY

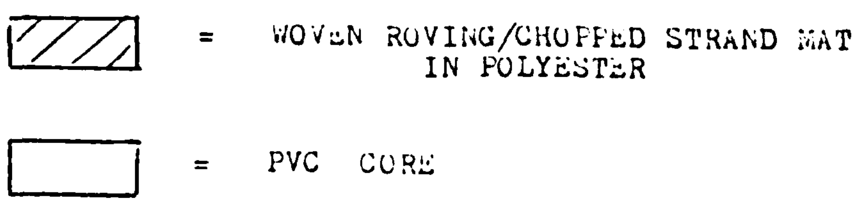
1. SANDWICH



2. SOLID

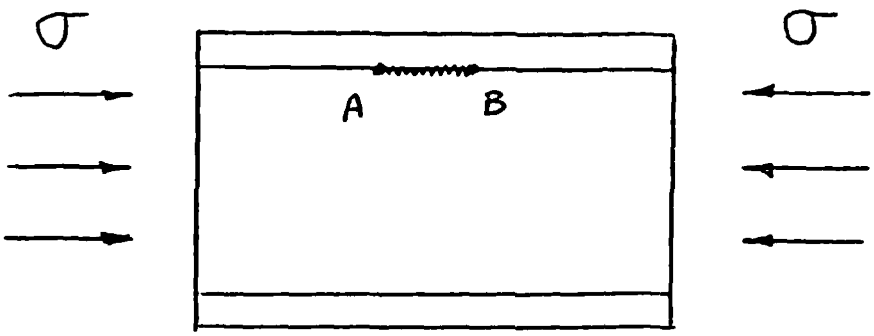


EI 1 = EI 2

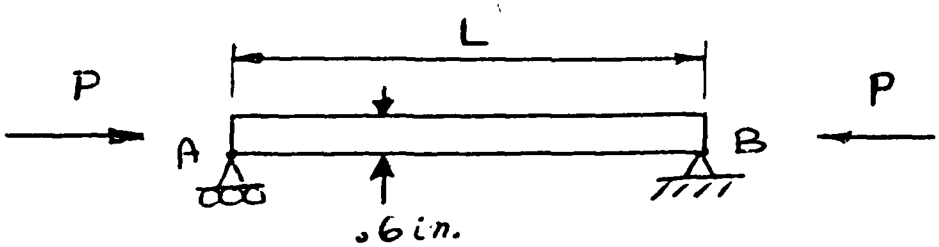


AFFENDIX F-3

ANALYSIS OF CRITICAL
DELAMINATION SIZE FOR INSTABILITY FAILURE



1. DELAMINATION @ INTERFACE A-B



2. FREE BODY DIAGRAM OF SKIN A-B

$\sigma = 2970 \text{ psi} \qquad P = 1782 \ \frac{\text{LB}}{\text{IN}}$

$E = 2.0 \times 10^{6} \text{ psi} \qquad I = .018 \ \frac{\text{IN}^4}{\text{IN}}$

EULER $\qquad P = \dfrac{\pi^2 E I}{(L_{CR})^2} \qquad \underline{\underline{L_{CR} = 14.1 \text{ in.}}}$

APPENDIX F-4

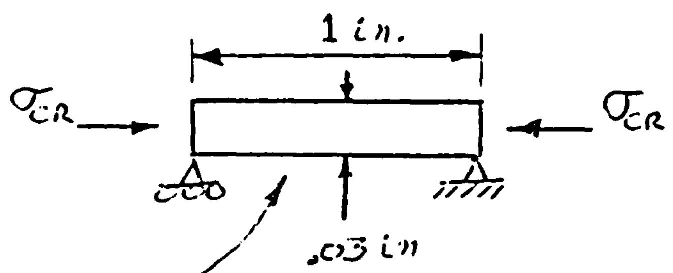
COMPARISON OF SIMPLE EULER BUCKLING PREDICTION WITH MORE SOPHISTICATED ANALYSIS

FOR A ONE INCH RECTANGULAR THROUGH WIDTH DELAMINATION:

EXPERIMENTAL RESULT [43] σ_{CR} = 25.560 psi
(Specimen as shown in Figure 24)

ANALYTICAL PREDICTION [43] σ_{CR} = 32.660 psi

SIMPLE EULER BUCKLING σ_{CR} = 18.505 psi
(Same geometry)



$I = 2.25 \times 10^{-6}\ in^4/in$
$E = 25.0 \times 10^{6}$ psi

$$\sigma_{CR} = \frac{\pi^2 EI}{AL^2}$$

Piece of skin above delamination

APPENDIX F-5

COMPARISON OF SIMPLE EULER PREDICTION WITH 2-D ANALYSIS

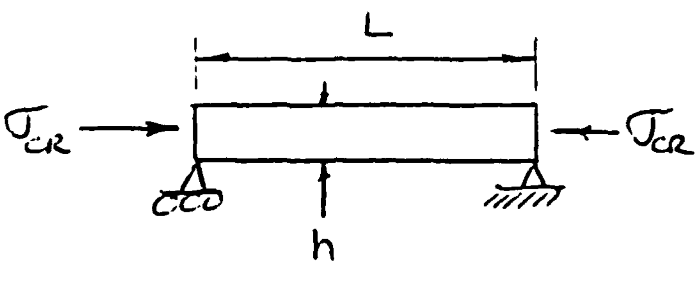
ANALYTICAL RESULTS FROM [44] PREDICT:
(Geometry shown in Figure 26)

2 IN. CIRCULAR DELAMINATON σ_{CR} = 10,000 psi

SIMPLE EULER BUCKLING ANALYSIS PREDICTS:

2 IN. RECTANGULAR DELAMINATION σ_{CR} = 2,267 psi

$$\sigma_{CR} = \frac{\pi^2 E I}{A L^2}$$



L = 2 IN.

h = .021 IN.

I = 7.72×10^{-7} in^4

E = 25×10^6 psi

APPENDIX F-6

INSTABILITY FAILURE AS A PER CENT OF COMPRESSIVE FAILURE STRESS

$$\sigma_{CR} = \frac{\pi^2 E I}{A L^2}$$

E = 2 X 10 psi
I = .018 in
A = .6 in

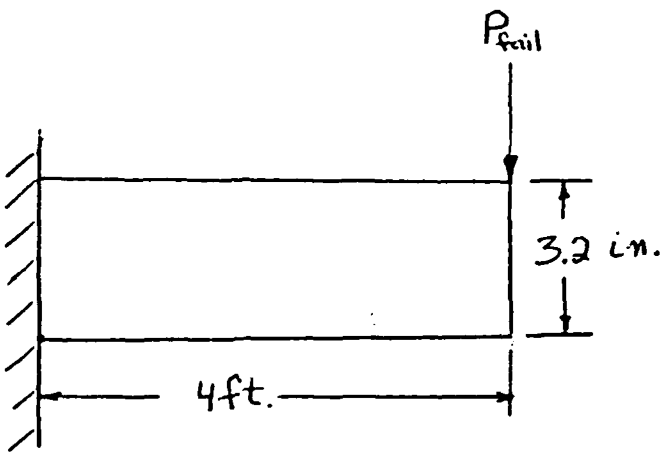
σ_{CR} (psi)	L (inch)	$\sigma_{CR}/\sigma_{COMP}$ (%)
1028	24.0	5.1
2970	14.1	14.8
4112	12.0	20.6
5922	10.0	29.6
9253	8.0	46.3
16449	6.0	82.2
19576	5.5	97.9

APPENDIX F-7

SUPPORTING CALCULATIONS FOR DELAMINATION MODELS

$$\sigma = \frac{PLy}{I}$$

LOCAL LOADING MODEL:



σ_{fail} = 20,000 psi

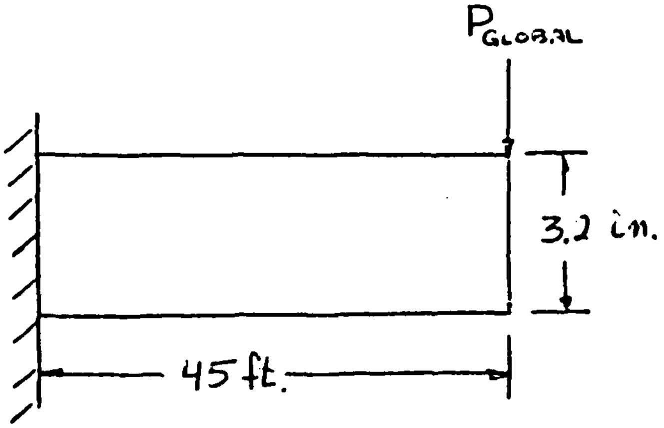
L = 48 in

I = 2.736 in

y_{max} = 1.6 in

$\therefore$ P_{fail} = 711 lbs

GLOBAL LOADING MODEL:



σ_{GLOBAL} = 2970 psi **

L = 45 ft.

I = 2.376 in

y_{max} = 1.6 in

$\therefore$ P = 9.4 lbs.

** Based on a once in 20 years bending load. See Figure 28.

APPENDIX F-7

SUPPORTING CALCULATIONS FOR DELAMINATION MODELS

USING A BASIC PROGRAM, THE CALCULATION OF CRITICAL LOAD WAS MADE FC? THE SHEAR PROPAGATION OF DELAMINATION MODEL [40]. THE FOLLOWING OUTPUTS ARE PROVIDED:

LOCAL
(see FIG 20)

BREAK IN 9 JPR#1 RUN ($\frac{a}{L}$)	a	P_{CRIT}	% P_{fail}
?.02	.960	537.56	76
?.03	1.44	393.36	55
?.04	1.92	314.69	44
?.05	2.40	262.35	37
?.06	2.88	242.07	32
?.07	3.36	194.54	27
?.08	3.84	170.97	24
?.10	4.80	135.73	19
?.20	9.60	59.08	8
?.40	19.20	22.7	3
	IN.	lbs.	

GLOBAL
(see FIG 21)

BREAK IN 9 JPR#1 RUN ($\frac{a}{L}$)	a	P_{CRIT}
?.05	27.0	21.93
?.06	32.4	18.44
?.07	37.8	15.75
?.08	43.2	13.62
?.09	48.6	11.91
?.10	54.0	10.51
?.109	58.9	9.45
	≈59	9.4
?.11	59.4	9.35
?.12	64.8	8.38
?.15	81.0	6.26
?.20	108.0	4.22
?.25	135.0	3.08
	IN.	lbs.

APPENDIX G-1

CALCULATION OF THE EFFECT OF ANISOTROPY ON STRESS CONCENTRATION FACTOR

FROM [45] THE STRESS CONCENTRATION FACTOR FOR AN INFINITE PLATE WITH A HOLE OF RADIUS R IS GIVEN BY:

$$K_T^{\infty} = 1 + n$$

$$n = \sqrt{2\left(\sqrt{\frac{E_y}{E_x}} - \nu_{xy} + \frac{E_y}{2G_{xy}}\right)}$$

FOR THE MATERIAL OF INTEREST :

$E_y = 3 \times 10$ psi

$E_x = 2 \times 10$ psi

$G_{xy} = .45 \times 10$ psi

$\nu_{xy} = .19$

$n = 2.9$ $\qquad$ $K^{\infty}_{T\,(ORTHO)} = 3.9$

$K^{\infty}_{T\,(ISO)} = 3.0$ $\qquad$ $\dfrac{K^{\infty}_{T\,(ORTHO)}}{K^{\infty}_{T\,(ISO)}} = 1.3$

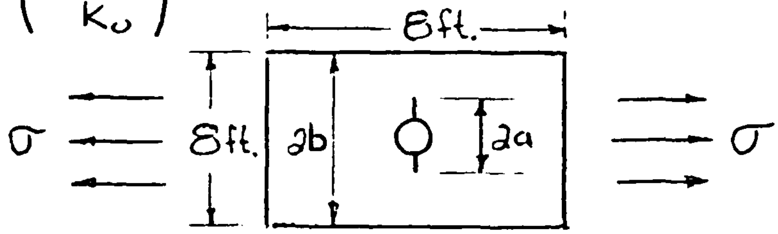
APPENDIX G-2

CALCULATION OF STRESS INTENSITY FACTOR FOR HOLES WITH CRACKS IN A FINITE PLATE

FROM [48] THE STRESS INTENSITY FACTOR FOR A HOLE WITH CRACKS IN A FINITE PLATE IS:

$$K_I = K_o\left(\frac{K_I}{K_o}\right)$$

$$K_o = \sigma\sqrt{\pi a}$$



$$K_{I_{ORTHO}} = 1.3\left(K_{I_{ISO}}\right)$$

$$\sigma = 2970 \text{ psi}$$

BY TRIAL AND ERROR:

R *	$\frac{R}{b}$	a *	$\frac{a}{b}$	K_o **	$\frac{K_I}{K_o}$	$K_{I_{ISO}}$ **	$K_{I_{ORTHO}}$ **
6	.125	10	.208	16.6	1.05	17.4	22.7
		7	.146	13.9	.85	11.8	15.4
		6.5	.135	13.4	.73	9.8	12.7
		6.6	.141	13.7	.80	10.9	14.2
12	.25	12.3	.255	18.4	.50	9.2	11.9
		12.5	.260	18.6	.65	12.1	15.7
		12.4	.258	18.5	.59	10.9	14.2
24	.50	24.3	.505	25.9	.43	11.0	14.3
		24.2	.504	25.9	.40	10.4	13.5
0	.0	4.3	.086	10.9	1.0	10.9	14.2

* INCHES

** $ksi\sqrt{in}$

APPENDIX G-3

EFFECT OF COMBINATIONS OF HOLE AND CRACK SIZES AS A PER CENT OF COMPRESSIVE FAILURE STRESS

[48] $$K_I = \frac{K_I}{K_o}\sigma\sqrt{\pi a} \qquad \sigma_{comp} = 20{,}000 \text{ psi}$$

$$\sigma_{fail} = \frac{K_I \dfrac{K_o}{K_I}}{\sqrt{\pi a}} \qquad \text{FOR } K_I = K_Q = 14 \text{ ksi}\sqrt{\text{IN}}$$

R (inches)	a (inches)	$\frac{K_I}{K_o}$	σ_{fail} (psi)	$\sigma_{fail}/\sigma_{comp}$ (%)
6	6.7	0.8	2970	14.9
6	10.0	1.05	1830	9.1
12	12.4	0.59	2970	14.9
12	12.5	0.65	2644	13.2
24	24.3	0.43	2903	14.5
12	15.0	1.12	1400	7.0
24	26.0	1.15	1030	5.2
0	2.0	1.0	4296	21.5
0	3.0	1.0	3508	17.5
0	5.0	1.01	2690	13.5
0	6.0	1.02	2432	12.1
0	8.0	1.02	2106	10.5
0	0.5	1.0	8592	42.9
0	0.3	1.0	11093	55.5
0	0.1	1.0	19213	96.1

GEOMETRY IS SHOWN IN FIGURE 30

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MIL-W-17549	GRP FOR MARINE STRUCTURES
MIL-R-21607D	POLYESTER RESIN
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